EQUINE VETERINARY EDUCATION/AMERICAN EDITION VOLUME 34 NUMBER 12 DECEMBER 2022

AAEP®

EQUINE VETERINARY EDUCATION

American Edition | December 2022

BEVA

The official journal of the American Association of Equine Practitioners, produced in partnership with BEVA.

IN THIS ISSUE:

SO INNOVATIVE...
IT'S LIKE MAGIC

Assure® Guard Gold
AND
AssureGuard® Gold NG

The Ultimate Digestive Aid®

THE REAL MAGIC IS IN THE RESULTS

Together, Assure Guard Gold-NG And Assure Guard Gold Create A Powerhouse Against Your Most Challenging Digestive Cases.

Use Assure Guard Gold-NG For Fast Relief And Maintain Excellent Digestive Health With Assure Guard Gold.

Replace your mineral oil, electrolytes, adsorbents, or other treatment options with Assure Guard Gold-NG the only effective and easy to administer slow gelling quick relief formulation including 2 cups of ultra pure psyllium, 72 billion CFU of probiotics, prebiotics, antacids, L-glutamine, electrolytes and energy.
For continued support, consider a 10 day supply of Assure Guard Gold after treatment.

ARENUS® ANIMAL HEALTH

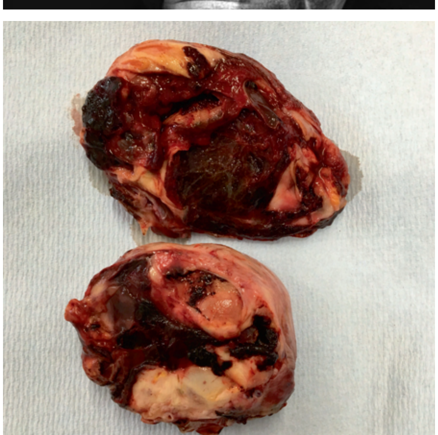
Arenus Animal Health | 866-791-3344 | www.arenus.com

Ask your Arenus Veterinary Solution Specialist how Assure Guard Gold-NG and Assure Guard Gold can help your equine patients quickly and effectively recover from the digestive upsets you treat daily.

EQUINE VETERINARY EDUCATION
AMERICAN EDITION

DECEMBER 2022 • VOLUME 34 • NUMBER 12

CONTENTS



AAEP NEWS In this issue

Cover photo by Dr. Nat White.

American Association of Equine Practitioners
4033 Iron Works Parkway
Lexington, KY 40511
TEL (800) 443-0177 • (859) 233-0147
FAX (859) 233-1968
EMAIL aaepoffice@aaep.org
aaep.org

To access our website, go to aaep.org, select LOGIN, then enter your email and password. If you have difficulty logging in or have forgotten your password, please call or email the office.

Published monthly. Deadlines are the seventh of the preceding month.
Address advertising inquiries to Dana Kirkland
(859) 233-0147 / dkirkland@aaep.org

AAEP Mission Statement: To improve the health and welfare of the horse, to further the professional development of its members, and to provide resources and leadership for the benefit of the equine industry.

EQUINE VETERINARY EDUCATION
AMERICAN EDITION
DECEMBER 2022 • VOLUME 34 • NUMBER 12

Equine Veterinary Education is a refereed educational journal designed to keep the practicing veterinarian up to date with developments in equine medicine and surgery. Submitted case reports are accompanied by invited reviews of the subject (satellite articles) and clinical quizzes. Tutorial articles, both invited and submitted, provide in-depth coverage of issues in equine practice.

Equine Veterinary Education (American Edition ISSN 1525-8769) is published monthly by the American Association of Equine Practitioners, an international membership organization of equine veterinarians. Office of publication is 4033 Iron Works Parkway, Lexington, KY 40511. Periodicals Postage paid at Lexington, KY and additional mailing office. POSTMASTER: Send address changes to: Equine Veterinary Education, 4033 Iron Works Parkway, Lexington, KY 40511.

Communications regarding editorial matters should be addressed to: The Editor, Equine Veterinary Education, Mulberry House, 31 Market Street, Fordham, Ely, Cambridgeshire CB7 5LQ, UK. Telephone: 44 (0) 1638 720250, Fax: 44 (0) 1638 721868, Email: sue@evj.co.uk.

All manuscript submissions for the journal should be submitted online at http://mc.manuscriptcentral.com/eve. Full instructions and support are available on the site and a user ID and password can be obtained on the first visit. If you require assistance, click the Get Help Now link that appears at the top right of every ScholarOne Manuscripts page.

All subscription inquiries should be addressed to: Subscriptions Department, AAEP, 4033 Iron Works Parkway, Lexington, KY 40511, Telephone: (859) 233-0147, Email: jcooney@aaep.org. Subscription rates: AAEP annual membership dues include $40 for a subscription to *Equine Veterinary Education*. Other subscriptions at $151.80. Single copies $37.50.

Canadian Subscriptions: Canada Post Corporation Number 40965005. Send change address information and blocks of undeliverable copies to AAEP, 1415 Janette Avenue, Windsor, ON N8X 1Z1, Canada.

Printed by: Sheridan, Hanover, PA.

From the president: Making the work fit the workforce

By Emma Read, DVM, MVSc, DACVS

Dr. Emma Read

The headlines are stark. It is anticipated that 42,000 veterinarians will be needed to meet the demands from retirement and industry growth in the U.S. small animal sector by 2030. This total doesn't even factor in the 25% of practitioners reportedly contemplating leaving the profession soon if nothing changes. Just how is that shortfall going to be covered?

Equine practice is no different and, unfortunately, perhaps worse off. Our shortage is not just projected, it is already here. It is estimated that by 2030 equine practice will require 5,300 veterinarians to meet growth and retirement demands (there are currently 3,645 practicing equine vets). Now remember that only 1.3% of all U.S. veterinary graduates enter equine practice directly, 4.5% enter internships and, during the first five years, 50% of them leave the profession. Currently, 30% of AAEP members are age 59 or older. The reality is that equine practice is a fraction of small animal practice but with a much larger problem.

It was against that backdrop that my presidential year began at the 2021 convention. At that board of directors meeting, the Retention Task Force shared data from months of interviews with practice owners, students, new graduates and early associates. The pain points they identified were clear, and our colleagues were suffering. Practice owners were struggling to hire and retain employees, while younger colleagues were having trouble finding a space where they felt like they belonged and could thrive.

Turning data into action

At our January board meeting, we formed an operational plan. The AAEP would focus on sustainability in equine practice as our No. 1 strategic priority and, over the next few years, change would be realized, collectively envisioned and developed by the members themselves. The ambitious plan included the following broad strokes:

- By convention in 2022, we wanted to leave no doubt that this issue had reached a critical level of importance and needed immediate action; gather colleagues together to target key areas and strategize possible solutions; and "come clean" by sharing the findings of the task force beyond veterinarians (i.e., with other organizations, horse owners and industry partners).
- By convention in 2023, we wanted to have members working on identified areas by developing solutions and programs to address core issues affecting sustainability.
- By convention in 2024, we wanted to champion solutions that make a difference and show positive impact; encourage others to take action so we can scale up across the organization (and profession); change the tone of equine practice; and most of all CHANGE THE NUMBERS (e.g., see more students entering equine practice, see a rise in students identifying their internship program as a positive educational experience, and see a decrease in the number of new graduates leaving in the first five years). We also envisioned that changes which need to be made will have a positive effect on practice culture and life balance for all of us.

By the end of the January meeting, we had convened two different task forces. The first, an internship task force, was asked to reimagine a true educational experience for new graduates and not one that simply capitalized on "cheap labor." The second task force focused on organizing a practitioner summit meeting, which was held in May in Dallas, Texas, with 20 practice owners from across the U.S. representing various backgrounds and sectors.

Focusing on five key areas

The themes identified at that summit meeting led to the formation of the Commission on Sustainability in Equine Practice, approved by the board in July. In August, the Member Engagement Committee and the officers established five subcommittees focused on compensation, emergency coverage, practice culture, internships, and veterinary students.

The compensation subcommittee's first task was to establish a reliable number for salary and benefits and a demonstrated pathway that new graduates could trust. A survey completed by more than 1,300 colleagues captured accurate information specific to equine practice in all sectors.

The internship task force became the internship subcommittee as they continued their work to transform the Avenues program into AAEP Grow. Their vision is to establish guidelines for best practices, a set of educational outcomes for all internships to offer, additional tools to help practices work with young colleagues, and a system to give interns finishing their program the opportunity to provide feedback to encourage other young vets to enter this intense period of preparation.

The veterinary student subcommittee was asked to scrutinize the relationship between AAEP members and students. What messaging do students receive and how

continued on next page

From the president, continued

can members play a more active role in sharing all the great things equine has to offer? How can practitioners provide skills opportunities and support for the next generation?

This problem is not going to be fixed by AAEP leaders creating the solutions and pushing them from the "top down." The solutions to our problems lay within each of us and within our practices, and it is reaching for ways to do things differently that will help even in the smallest of ways.

The emergency coverage subcommittee was tasked with identifying and cultivating alternative models to manage emergency work and sharing these more broadly with members.

Meanwhile, the practice culture subcommittee was tasked with defining what makes up the "culture" of equine practice and how best to empower practice owners to prioritize health and welfare of all staff without compromising client care or the economics of the practice. How can we do what we do, but do it smarter and in a way that looks after everybody?

In addition to the Commission, the board has established funding to assist young colleagues wanting to participate in mentorship programs like Decade One or MentorVet. The board has also created a Horse Owner Education Committee, and I wrote a couple articles targeting horse owners and the industry at large.

Contributing in your own way

We are already one year into our efforts and one year closer to the 2030 projections, which feels unsettling except for the fact we are starting to make change. I have been extremely honored to serve as your president and to play a small part in getting this very large rock rolling down the hill. Now as we are picking up momentum, we will need all of you.

This problem is not going to be fixed by AAEP leaders creating the solutions and pushing them from the "top down." The solutions to our problems lay within each of us and within our practices, and it is reaching for ways to do things differently that will help even in the smallest of ways. It will be the innovation and dedication of each person in wanting to change the numbers and build beyond what we already have. Just as equine seemingly led the way into the abyss, I am positive that we will be the ones to effectively lead the way out. We can do this but we will have to work together—a tough order for a bunch of hard working, fiercely independent, and really busy people!

I leave you with this thought that I heard while attending the British Equine Veterinary Association Congress in September as your representative. During a discussion among roughly 30 presidents and executive directors from many of the global equine associations, every single one noted that sustainability is their top strategic priority. BEVA President Dr. Huw Griffiths summed it up well when he said that this was all about "making the work fit the workforce, rather than making the workforce fit the work." If every member starts there, we can transform the numbers and change the headlines associated with our profession. Thank you for the opportunity of a lifetime.

Help equine rescue and retirement facilities apply for free vaccines

2023 UHVRC application deadline is February 1

AAEP members affiliated with 501(c)(3) equine rescue and rehabilitation facilities in the United States should work with those facilities now to complete the application for complimentary vaccines from the Unwanted Horse Veterinary Relief Campaign (UHVRC) by the Feb. 1 deadline.

The UHVRC is a non-profit partnership between Merck Animal Health and the AAEP to safeguard the health and facilitate the adoption of rescue horses. Since its inception in 2008, the UHVRC has provided more than 46,000 doses of core vaccines to protect horses in need.

The UHVRC provides qualifying equine facilities with vaccines to protect against Eastern and Western equine encephalomyelitis, equine rhinopneumonitis (EHV-1 and EHV-4), West Nile virus, equine influenza, tetanus and rabies. Eligible facilities must coordinate an application with an AAEP-member veterinarian and adhere to the AAEP Care Guidelines for Equine Rescue and Retirement Facilities.

Visit aaep.org/horse-owners/unwanted-horse-veterinary-relief-campaign to download the application and equine vaccine order form.

UHVRC
Unwanted Horse Veterinary Relief Campaign

5 things to know about AAEP this month

1. Acquire indefinite on-demand access to all convention educational sessions and earn CE until March 31, 2023, through virtual registration at convention.aaep.org.
2. Enjoy free access until Feb. 13 to all the *EVE* and *EVJ* articles highlighted during the Kester News Hour and cited in the Milne Lecture at https://tinyurl.com/mr3ktyse.
3. Relax and recharge for the year ahead at the Resort Symposium in Grand Cayman, Jan. 23–25, 2023. Register at aaep.org/meetings/resort-symposium.
4. Provide up to $600 worth of free veterinary services to at-risk animals by signing up for The Foundation's Vet Direct Safety Net program at aaep.org/vet-direct-safety-net.
5. Become more involved with the AAEP in 2023 by completing the Volunteer Interest Form accessible at aaep.org/dashboard.

Learn and earn with virtual convention registration

Were you unable to join your colleagues in San Antonio for the AAEP's 68th Annual Convention? If so, no worries. You can take advantage of virtual registration and receive indefinite on-demand access to all educational sessions.

CE hours from on-demand sessions can be earned through March 31, 2023. Register and view the complete educational program at convention.aaep.org.

As a reminder, if you were an on-site attendee, you receive the virtual option at no additional cost.

Nominate a distinguished researcher for the 2024 AAEP Milne Lecture

Deadline to nominate is January 31

The Frank J. Milne State-of-the-Art Lecture is a traditional highlight of each year's annual convention, and you can help determine the 2024 honoree by nominating an accomplished researcher.

The Milne Lecture was created in 1997 to recognize an individual with a distinguished career in research and discovery, and who has presented and published their findings in a specific area of equine health. The lecture is intended to honor the accomplishments of the presenter and provide a meaningful learning experience to the AAEP membership. The lecture is a perspective on the state-of-the-art in the presenter's area of expertise.

The award recipient will be determined by a subcommittee of the AAEP Educational Programs Committee in February 2023 and will then be presented to the board of directors for approval. The selected individual will deliver their lecture and receive their award at the AAEP's 2024 Annual Convention in Orlando, Fla.

Nominees should be an expert in their field with a track record of accomplishment and the ability to relate the

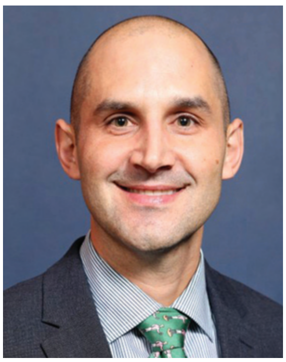
Dr. Jean-Marie Denoix delivers the 2021 Milne Lecture on the topic of lameness.

topic to the audience. A nomination form must be completed and include qualifications and accomplishments of the nominee.

A Milne Lecture nomination form may be requested from Carey Ross, scientific publications coordinator, at cross@aaep.org. Completed forms must be returned to her by Jan. 31, 2023.

Ethical equine practice begins with a strong foundation and training

By Ernie Martinez II, DVM, MBA



Dr. Ernie Martinez

Practicing high-quality equine medicine can be a challenging career path. After completing veterinary school and successfully passing boards, young veterinarians are eager to get out into the world and practice medicine, diagnose cases, devise treatment plans, and consult with mentors and specialists. Added unwanted challenges can arise when veterinarians are placed in complex scenarios that may confront their ethics.

To prepare new graduates and young doctors on how to handle ethically challenging situations, an equine veterinary ethics program introduced from day one can provide the training and tools to set the foundation for a career in ethical equine practice. An equine veterinary ethics program should include defined written standards, training programs, reporting mechanisms and violations policy, and a strategy for periodic assessment.

Defined written standards will clarify and educate all employees—practitioners and support staff—on the ethics and values of the practice as well as employee expectations. The ethics of a practice are the principles, norms and standards that govern a group. Practice ethics can be found in mission and value statements commonly presented in employee handbooks. Often these go hand-in-hand with the morals, principles and rules we follow as individuals. Practice ethics are defined by practice leadership and have a huge impact on determining the culture of an organization. Once defined, written standards of ethical conduct should be shared during the onboarding and orientation of new veterinarians and staff.

Successful ethical practices should utilize an ethics training program to further educate and train the individuals in a practice most likely to face complex ethical challenges. An internal assessment can help identify ethical dilemmas and those most likely to be challenged. In most cases, this is likely to be a doctor asked to provide unethical treatments or procedures, but a staff member may also be challenged ethically with regard to records, invoices, client communications or by assisting in unethical treatments or procedures. The training program and educational materials should be shared with doctors and staff on a regular basis, such as annual reviews or performance evaluations. By providing tools such as an ethical decision-making model, ethics and ethical practice will remain on the minds of all team members.

A key component of an ethics training program is highlighting and clearly defining the proper reporting mechanisms doctors and staff should take when faced with ethical issues or challenges. Young veterinarians may rely on a mentor or senior clinician, but in certain circumstances, a non-veterinarian resource may be better. This may include a practice manager or medical director, but the most appropriate resource is a human resources specialist trained to address these issues. If the practice size or model does not include an HR specialist, there are resources available through the AAEP and the AVMA that can provide the proper channel for a young practitioner to seek help with an ethical challenge. These resources may serve as an ombudsman and facilitate a fair resolution acting in the capacity of a neutral third party.

Practice ethics are defined by practice leadership and have a huge impact on determining the culture of an organization.

When ethical violations are identified, a violation policy ensures that punishments are handed down fairly. Punishments may include internal fines, loss of titles, decreased leadership roles and possible repercussions from veterinary licensing bodies. A strategic schedule for an annual review of the ethical compliance of an organization should be created to assess the performance and success of an ethical training program.

Ethical challenges will arise in equine medicine. Successful leadership presents a forceful tone from the top to define the ethical standards of the practice. Those who incorporate an equine veterinary ethics program into the culture of their practice will best prepare their doctors and staff for ethical challenges. An ethics program with defined values, guidelines, penalties and open discussions about veterinary ethics will enhance the reputation and goodwill of the practice and, ultimately, make it a more successful and welcoming place to practice.

AAEP ETHICAL PRACTICE Every Day-Every Time

Dr. Martinez is a field care veterinarian at Hagyard Equine Medical Institute in Lexington, Ky., and a member of the AAEP's Professional Conduct and Ethics Committee as well Scientific Review and Editorial Committee.

Vet Direct Safety Net provides the gift of a peaceful passing

The Foundation–AAEP–ASPCA partnership can support a humane end to a dire situation

Dr. Shannon Subasi, owner of Los Alamos Equine Veterinary Services in northern New Mexico, enjoys seeing horses throughout their various life stages. At least one reunion with a former patient, however, was anything but a joyous occasion.

Dakota had been a valued companion at a local therapeutic riding program while under Dr. Subasi's care before joining the Luffel family to teach their children the ropes of riding. Although they were not regular clients, the Luffels contacted Dr. Subasi months later—in December 2021—requesting emergency care for Dakota.

The gelding had fallen and remained down when Dr. Subasi arrived. The family was deeply distressed and hopeful for a positive outcome. "We tried to diagnose what was wrong with him and, understandably, the owners wanted a clear diagnosis, which is sometimes hard," said Dr. Subasi. "We tried taking radiographs of his distal femur and stifle to see if there might be a fracture there."

Dr. Subasi doesn't have an ultrasound—she refers more-intense cases that may need treatments and modalities that are difficult to complete in the field. Sending Dakota to the clinic, however, was not an option financially for the Luffels.

"With a 1,000-pound horse, there are limitations to [what] radiographs [can show] in the field. The owners wanted to give him a chance and he was willing to try to stand, so we stood him up," Dr. Subasi explained. "I tried to palpate him rectally and could not find an obvious step. I said it was possible that he slipped and had nerve damage that was resulting in the way he was holding his leg and unable to bear weight, but that a fracture was likely."

To make Dakota more comfortable while locating a field ultrasound, Dr. Subasi administered nonsteroidal anti-inflammatories for a few days. The reprieve—for both Dakota and his owners—was desperately needed as the Luffels had rushed their 3-year-old child to the emergency room with a brain mass the same day Dakota went down.

Searching for a way to financially assist the family, Dr. Subasi came across the Vet Direct Safety Net program while reading *Equine Veterinary Education*. She immediately emailed the AAEP for more information on the program. After a 15-minute onboarding and minimal paperwork, she knew she could alleviate at least some of the family's financial concerns.

Dr. Shannon Subasi

"Unfortunately, Dakota deteriorated after a few days and went down again," said Dr. Subasi. "At this point, he was unwilling to rise and the owners agreed to euthanize him."

Though a heartbreaking decision to make, the availability of Vet Direct Safety Net funds allowed the Luffels the financial flexibility to see if Dakota could heal before making the decision to euthanize him. Designed to reduce the number of horses relinquished to rescues or sent to auction, the program reimburses up to $600 worth of free veterinary services per horse to assist owners with horses in need of emergency stabilization procedures, euthanasia or disposal.

"I would absolutely recommend this program to other vets," she said. "I do feel the program helped the Luffels enormously. We all are in this because we want to help horses—money should not be the reason that horses don't get the care they need. Life happens sometimes and the money isn't there when you need it, especially in times of emergency."

Though unable to save Dakota, the Luffels appreciated the availability of Vet Direct Safety Net funds to offer their beloved gelding a chance and, eventually, relieve him of his suffering. They even hired Dr. Subasi as veterinarian for their pony.

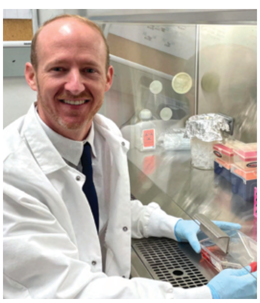
If you are an AAEP-member veterinarian in the United States with clients who may be struggling to pay for veterinary care, put yourself in a position to help by enrolling in the Vet Direct Safety Net program. Sign up or learn more by visiting aaep.org/vet-direct-safety-net or contacting Sue Stivers at sstivers@aaep.org.

Foundation supports six impactful equine research projects

The Foundation for the Horse has awarded $110,277 for six innovative equine research projects conducted by AAEP-member graduate students, residents or postdoctoral fellows. Over the last four years, The Foundation has provided $436,675 to support meaningful equine research by up-and-coming investigators as it continues to help pioneer medical advances in equine health.

For the third consecutive year, The Foundation was joined by the Thoroughbred Education and Research Foundation in helping make these research projects possible. This year TERF, whose mission is to make racing safer through research and education, increased its support by funding three important research projects with the potential to impact the health and safety of Thoroughbred athletes.

The supported research projects with researcher names and brief summaries follow:



Dual licensing of mesenchymal stem cells to enhance tendon healing *(TERF sponsored)*

Dr. Drew W. Koch, North Carolina State University

Utilize in vitro co-culture assays to determine if IL-1b and/or TGF-b2 licensed mesenchymal stem cells (MSC) positively affect equine superficial digital flexor tendon tenocyte growth, function, and expression of tendon-relevant genes and proteins to support future in vivo studies examining licensed MSC therapy for equine tendon injury.

In vitro analysis of the optimization of stem cell therapy for the treatment of osteoarthritis using equine synovial fluid derived from mesenchymal stem cells with a soluble epoxide hydrolase inhibitor *(TERF sponsored)*

Dr. Alexandra Carlson, University of Tennessee

To determine if using soluble epoxide hydrolase inhibitors (sEHi) with stem cell therapy can improve stem cell activity by reducing inflammation in the joint while also eliminating adverse effects on the stem cells that typical anti-inflammatory treatment can have.

Clinical evaluation of a rapid test strip, PCR, and enriched-aerobic culture for the detection of *salmonella enterica* in equine feces

Dr. Emily Herring, University of Georgia

Evaluate the rapid test's performance, compared to culture and PCR, for the detection of salmonella in equine fecal samples by performing all three tests in parallel on the same samples to assess their ability to determine whether a horse is infected with salmonella correctly.

Short-term oil dietary supplementation affects oocyte and cumulus cell metabolism in old mares

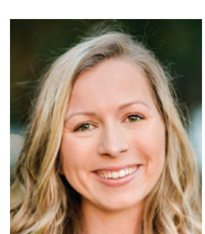
Dr. Giovana Di Donato Catandi, Colorado State University

Investigate how oils rich in omega-6 or omega-3 fatty acids affect the metabolic function of the oocyte and ovarian follicle cells and determine if additional dietary supplements can optimize fatty acid use in the ovarian follicle while reducing potential side effects.

A pilot study on an experimental model for Palmar Osteochondral Disease (POD) in horses *(TERF sponsored)*

Dr. Lauren Smanik, Colorado State University

To develop an experimental model of Palmar Osteochondral Disease (POD) that would allow researchers to study the progression in a controlled, prospective manner that will allow for future studies on variables that may affect lesion severity and facilitate the development of an optimized treatment plan.



Investigation of MARCKS protein as a novel therapeutic target to decreased neutrophil extracellular traps (NETs) in equine asthma

Dr. Bethanie L. Cooper, North Carolina State University

To identify novel treatment alternatives to steroid therapy for horses with equine asthma through neutrophil extracellular traps, released by airway neutrophils, as potential therapeutic targets.

Equine research is one of three pillars of impact—along with education and horses at risk—supported by The Foundation. The 2023 application window for this research grant program will open next spring. To learn more, visit https://tinyurl.com/ffthgsrrg.

California dreamin': Share your research at the 2023 convention in San Diego

Presenting authors receive free registration, honorarium

With thousands of practitioners, students and techs returning home from San Antonio with new ideas, solutions and skills to improve patient care and personal well-being, it's time to prepare for 2023 by submitting papers to be considered for presentation during the 69th Annual Convention in San Diego, Calif., Nov. 29–Dec. 3. The presenting author of selected papers will receive complimentary registration and an honorarium.

Eligible for consideration are scientific papers, how-to papers, review papers, abstracts, and business and lifestyle papers. All paper presentations are limited to 15 minutes with an additional 5 minutes for Q&A.

Submit papers by March 15 at https://s3.goeshow.com/aaep/annual/2023/aaep.cfm. Authors should visit the site in advance to set up a profile and provide paper and author information before uploading the paper when it is finished. Complete considerations and ethical guidelines are available in the General Instructions area of the site.

As an aid to private practitioners, first-time authors or members seeking guidance with their submission, AAEP offers a mentorship program in which experienced presenters are available to provide advice and direction. However, mentors are not responsible for rewriting or selecting material. Contact Carey Ross, scientific publications coordinator, at cross@aaep.org for a list of available mentors or with questions concerning educational paper submission.

Members in the News

Dr. Gregg Veneklasen named PRCA Veterinarian of the Year


Dr. Gregg Veneklasen

Dr. Gregg Veneklasen, founding owner of Timber Creek Veterinary Hospital in Canyon, Texas, has been named the 2022 Professional Rodeo Cowboys Association Veterinarian of the Year for his commitment to the health and welfare of rodeo livestock. He received his award Nov. 30 at the PRCA Awards Banquet in Las Vegas.

Dr. Veneklasen, who received his veterinary degree from Colorado State University in 1983, has worked with the Frontier Rodeo Company for 15 years. He cares for many of their top bucking horses and has cloned some of the best in an effort to keep the genetics viable for years to come.

Dr. Melissa Hines receives Ohio State alumni award


From left: Dr. Rustin Moore, OSU CVM dean; Dr. Melissa Hines; and Dr. Chrissie Schneider, OSU CVM Alumni Society president.

Dr. Melissa Hines, professor of large animal clinical sciences at the University of Tennessee College of Veterinary Medicine, has received an Alumni Recognition Award from The Ohio State University College of Veterinary Medicine Alumni Society for her contributions to the veterinary medical profession.

A veterinary graduate of 1980 who served on the AAEP's Member Engagement Committee from 2015–2017, Dr. Hines has special interest in immunology and infectious disease. She has authored or co-authored 65 peer-reviewed publications and numerous book chapters, and she has spoken frequently at national and international CE meetings. In addition, Dr. Hines has trained more than 45 interns and nearly 20 residents.

Dr. Sara Langsam appointed to HISA advisory group


Dr. Sara Langsam

Dr. Sara Langsam, shareholder at Teigland, Franklin & Brokken DVMs, Inc., who started the practice's Long Island, N.Y., division in 2012, is among 19 individuals selected to serve as members of the Horseracing Integrity and Safety Authority's inaugural Horsemen's Advisory Group. The group convenes monthly to provide feedback to the Authority's executive team and standing committees on the implementation and evolution of HISA's Racetrack Safety and Anti-Doping and Medication Control regulations.

Dr. Langsam is the new chair of AAEP's Racing Committee, on which she has served since 2018. She has also been a member of the Educational Programs and the Professional Conduct and Ethics committees. Dr. Langsam received her veterinary degree from the University of Pennsylvania in 2002.

Dr. Fairfield Bain honored by Auburn CVM


Dr. Fairfield Bain

Dr. Fairfield Bain, associate director of the Equine Life Cycle Management team at Merck Animal Health, received the John Thomas Vaughan Equine Achievement Award. The award recognizes an Auburn College of Veterinary Medicine alumnus who exemplifies the Auburn spirit through leadership, dedication to and passion for the profession, hard work that improves individual and community outcomes, and humility.

Dr. Bain received his veterinary degree in 1983. Prior to joining Merck in 2016, Dr. Bain's career included time in private referral hospitals as well as university hospitals in the U.S. and Australia. He is a longtime AAEP member and served on the Computer Applications Committee in the late 1990s.

Dr. Rick Mitchell named distinguished alumnus


Dr. Rick Mitchell

Dr. Rick Mitchell, co-founder and partner-owner of Fairfield Equine Associates in Newtown, Conn., has been named a 2022 Distinguished Alumnus Award recipient by Oklahoma State University College of Veterinary Medicine.

Dr. Mitchell, who received his veterinary degree in 1974, has served as an official veterinarian for the United States Equestrian Team at six Olympic Games and volunteered his leadership in service to the AAEP and broader equine industry. He served the AAEP on its board of directors and on 10 different councils and committees, including currently as chair of The Foundation Development Council and member of the Finance and Performance Horse committees. In addition, Dr. Mitchell is chair of the American Horse Council Board of Trustees and has served on the boards of the United States Equestrian Federation and other organizations.

INDUSTRY

AAEP Educational Partner Profile: Cargill

Cargill Feed & Nutrition, an Educational Partner of the AAEP since 2001, is committed to translating nutrition research into feed solutions that improve the health of horses. Cargill's rich history of creating innovative equine nutrition solutions includes our Nutrena®, Progressive Nutrition®, and ProElite® brands of feeds and supplements.

We believe a horse's topline plays an important role in how a horse performs, looks, and feels. Our industry leading topline assessment tool and a wealth of resources about topline health can be found at toplinebalance.com.

When it comes to nutrition that supports the health of your clients' horses, Cargill's team of equine nutrition experts is here to help you. Please visit our exclusive equine veterinarian website vetnutritioninfo.com where you will find resource to help your staff and your clients. If you have questions or a need for training and assistance, please contact us at 1-800-367-4894 or visit our website.

MEMBERSHIP

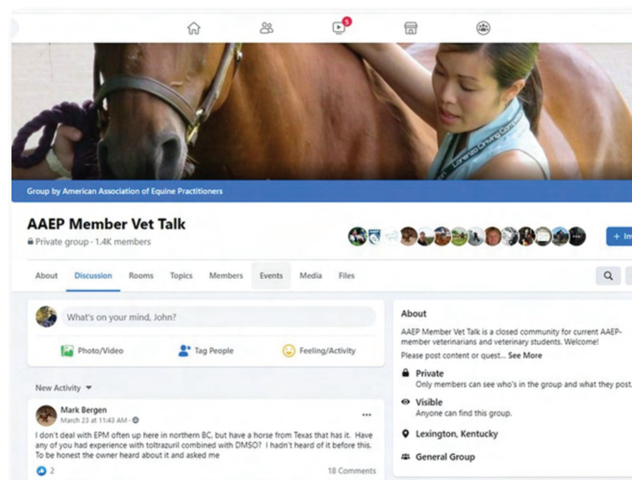
Benefit: Enlist colleagues' expertise in AAEP's online communities

Whether seeking advice on a difficult case, perplexed by an ethical dilemma, or wanting to offer support or guidance, you can draw upon the collective expertise of the membership through the AAEP's online communities.

One component of this complimentary benefit of your membership is the Rounds, which are online forums centered on specific topics and an ideal way to share ideas and knowledge with colleagues. You may subscribe to any of the following Rounds:

- Business Education
- Complementary & Alternative Medicine
- Dentistry
- Equitarian
- Infectious Disease
- New Practitioner
- Performance Horse
- Podiatry
- Public Auction
- Purchase Exam
- Racing
- Reproduction/Perinatology
- Solo Practitioner
- Wellness & Family Life

You may also subscribe to the General Discussion List, which is open to all topics of interest. To join any of the discussions, visit communities.aaep.org/home.



In addition to the Rounds, the AAEP Member Vet Talk community on Facebook is another forum to solicit or offer case advice or simply share content relevant to equine medicine. More than 1,600 members participate in AAEP Member Vet Talk. To join this AAEP members-only community, simply search for the group on Facebook.

There's nothing else like it.

For more than 30 years, Adequan® i.m. (polysulfated glycosaminoglycan) has been administered millions of times[1] to treat degenerative joint disease, and with good reason. From day one, it's been the only FDA-Approved equine PSGAG joint treatment available, and the only one proven to:[2, 3]

Reduce inflammation
Restore synovial joint lubrication
Repair joint cartilage
Reverse the disease process

When you start with it early and stay with it as needed, horses may enjoy greater mobility over a lifetime.[2, 4, 5] Discover if Adequan is the right choice. Visit **adequan.com/Ordering-Information** to find a distributor and place an order today.

BRIEF SUMMARY: Prior to use please consult the product insert, a summary of which follows: **CAUTION:** Federal law restricts this drug to use by or on the order of a licensed veterinarian. **INDICATIONS:** Adequan® i.m. is recommended for the intramuscular treatment of non-infectious degenerative and/or traumatic joint dysfunction and associated lameness of the carpal and hock joints in horses. **CONTRAINDICATIONS:** There are no known contraindications to the use of intramuscular Polysulfated Glycosaminoglycan. **WARNINGS:** Do not use in horses intended for human consumption. Not for use in humans. Keep this and all medications out of the reach of children. **PRECAUTIONS:** The safe use of Adequan® i.m. in horses used for breeding purposes, during pregnancy, or in lactating mares has not been evaluated. For customer care, or to obtain product information, visit www.adequan.com. To report an adverse event please contact American Regent, Inc. at 1-888-354-4857 or email pv@americanregent.com.

Please see Full Prescribing Information at *www.adequan.com*.

Start with it. Stay with it.®

Adequan i.m.®
polysulfated glycosaminoglycan
www.adequan.com

1 Data on file.

2 Adequan® i.m. Package Insert, Rev 1/19.

3 Burba DJ, Collier MA, DeBault LE, Hanson-Painton O, Thompson HC, Holder CL: In vivo kinetic study on uptake and distribution of intramuscular tritium-labeled polysulfated glycosaminoglycan in equine body fluid compartments and articular cartilage in an osteochondral defect model. *J Equine Vet Sci* 1993; 13: 696-703.

4 Kim DY, Taylor HW, Moore RM, Paulsen DB, Cho DY. Articular chondrocyte apoptosis in equine osteoarthritis. The Veterinary Journal 2003; 166: 52-57.

5 McIlwraith CW, Frisbie DD, Kawcak CE, van Weeren PR. Joint Disease in the Horse.St. Louis, MO: Elsevier, 2016; 33-48.

EQUINE VETERINARY EDUCATION
Equine vet. Educ. (2022) **34** (12) 618-619
doi: 10.1111/eve.13729

Highlights of recent clinically relevant papers

Equine influenza epidemic

An epidemic of equine influenza (EI) occurred in Europe in 2019. This retrospective study by Fleur Whitlock and co-workers in the UK and South Africa described the epidemiology of this epidemic within Great Britain.

Epidemiological data were obtained from veterinary surgeons referring samples for EI virus testing. Where available, data on confirmed cases and their wider resident population on EI-infected premises were collated and described. On a national level, spatial and temporal representations, consisting of choropleth maps and epidemic curves, described the spread of EI. EI-infected premises-level factors associated with the first of two epidemic phases were investigated using ordinary logistic regression analysis.

There were 412 confirmed cases and 234 EI-infected premises, with the first of two epidemic phases occurring between January and April, followed by a second phase through to August. The median age of confirmed cases was 5 years, and sports horses (24%) and Cobs (16%) made up the highest proportions by general horse type and breed. Among confirmed cases, 72% were unvaccinated and 18% were vaccinated against EI. New horses arriving within 2 weeks of a confirmed case were reported by 42% of EI-infected premises. Investigation of EI-infected premises' biosecurity measures indicated that 23% quarantined new arrivals, 37% had isolation facilities and 57% of resident horses were vaccinated. EI-infected premises were more likely in the first than second epidemic phase to be classified as professional, have a vaccinated confirmed case and EI confirmed in a newly arrived animal. EI-infected premises generally had low levels of population vaccine coverage and implemented limited preventive biosecurity measures, particularly linked to horse movements.

Gut health in horses

The conventional feeding management of horses is still characterised by high-starch and low-fibre diets, which can negatively affect gastrointestinal health. The aim of this study by Elena Colombino and co-workers in Italy and Germany was to compare the effects of a high-starch (HS) vs. a high-fibre (HF) diet on gut health in horses.

A total of 19 Bardigiano horses destined for slaughter (aged 14.3 ± 0.7 months) were randomly allotted to two dietary groups: HS (5 fillies and 4 colts) and HF group (7 fillies and 3 colts). They received the same first-cut meadow hay but different complementary feeds for 72 days: HS group was fed 8 kg/animal/day of a starch-rich complementary feed while HF group was fed 3.5 kg/animal/day of a fibre-rich complementary feed. At slaughter, stomachs were separated and washed for the evaluation of the glandular and squamous regions. Also, duodenum, jejunum, ileum, apex of the caecum, sternal flexure, pelvic flexure, right dorsal colon, rectum and liver were excised and submitted to histomorphometrical evaluation.

The glandular region of the HS group presented more severe gastric mucosa lesions compared with the HF group. A statistical tendency was also found for the squamous region, presenting a higher score in the HS than HF diet. Regarding morphometry, in jejunum villus height to crypt depth (Cd) ratio was influenced by sex, being greater in males than in females while in ileum Cd depended on interaction between sex and diet, being greater in the HS group males. In addition, in the duodenum and right dorsal colon, the severity of the inflammation depended on sex, being greater in females than in males. In contrast, in the jejunum and in the pelvic flexure, inflammation was influenced by diet, being more severe in the HS than in the HF group.

These results suggested that HS diet provoked more severe mucosa lesions in the glandular region of the stomach and a higher inflammation both in the jejunum and pelvic flexure. The authors concluded that this study could represent a starting point for further investigations on gut health in horses.

Subpalpebral lavage treatment systems

This retrospective study by Emilie Quéré and Sabine Chahory, based in France, described the outcomes and complications associated with the location of subpalpebral lavage (SPL) treatment systems, in the superior or inferior eyelid in horses.

Clinical records of all horses admitted to the National Veterinary School of Alfort over an 18-year period, in which a SPL treatment system was used to administer topical ophthalmic medications, were reviewed. Sixty horses were included in the study representing 61 SPL treatment systems. Uneventful outcomes occurred in 53 cases (86.9%), and complications were recorded in 8 cases (13.1%). Seven complications were reported for upper eyelid systems (23.3%) and one complication for lower eyelid systems (4.2%). The complication rates were not significantly different between these two locations.

The complications identified were iatrogenic corneal ulceration, palpebral abscess, overgrowth of conjunctiva over the footplate and palpebral cellulitis. Median duration of SPL treatment system use was 7.5 days. The easier placement and removal and the lower incidence of complications identified in this study has encouraged the authors to favour the lower fornix for subpalpebral lavage treatment systems within their equine hospital.

Vitamin D status in horses

The aim of this cross-sectional cohort study by Miranda Dosi and co-workers in the UK was to determine the relationship between management, season and endocrine disease and vitamin D status in horses.

Plasma concentrations of 25-hydroxyvitamin D_2 (25[OH]D_2) and D_3 (25[OH]D_3) were measured by liquid chromatography–tandem mass spectrometry in 34 healthy unsupplemented grazing ponies, and 22 stabled Thoroughbreds receiving supplementary vitamin D_3 in feed. A nested group of 18 grazing ponies were sampled on long and short days (>12 and <12 h of light/day) to determine the effect of sunlight exposure. Additionally, the relationships between age, sex, adiposity, serum insulin, adrenocorticotropic hormone and vitamin D status were assessed in a mixed group of 107 horses using a linear regression model.

All animals had measurable levels of 25(OH)D_2 (median 10.7 nmol/L) while 25(OH)D_3 was only detected in Thoroughbreds receiving D_3 supplementation. Thoroughbreds had lower concentrations of 25(OH)D_2 than ponies (7.4 nmol/L vs. 12.6 nmol/L). In grazing ponies, 25(OH)D_2 concentrations were significantly higher on long days compared with short days (14.4 nmol/L vs. 8.7 nmol/L), while 25(OH)D_3 was undetectable. Measures of increased adiposity, but not basal insulin, were associated with higher 25(OH)D_2 concentrations, conversely to humans. Increasing ACTH was associated with lower 25(OH)D_2.

In horses, 25(OH)D_2 is the predominant vitamin D metabolite, and there is an apparent lack of endogenous vitamin D_3 production. The relationship between vitamin D and endocrine disorders in horses does not reflect that of other species.

Venous lactate after colic surgery

This prospective clinical study by Lauren Smanik and co-workers in the United States evaluated venous lactate measurements in horses following colic surgery and aimed to determine whether lactate concentrations were significantly higher in horses that developed postoperative complications or did not survive to hospital discharge.

Horses >1 year of age undergoing surgery for colic and recovered from general anaesthesia were sampled. A portable lactate meter was used to measure venous samples collected immediately following anaesthetic recovery and daily throughout hospitalisation. Complications arising during hospitalisation and survival to hospital discharge were recorded.

Fifty-one horses were enrolled, aged from 2 to 29 years. Lactate concentration immediately following anaesthetic recovery was higher in horses that developed complications during hospitalisation. The odds of developing complications postoperatively were doubled for horses with a venous lactate concentration >5 mmol/L. Lactate measurements in non-survivors were significantly higher compared with survivors by 96 h postoperatively.

Higher venous lactate concentrations in the postoperative colic period were associated with an increased risk of complications and death. Results suggest horses with higher venous lactate measurements in recovery are more likely to have postoperative complications, with the odds of developing complications doubled for horses with a venous lactate >5 mmol/L. Evaluation of venous lactate could provide information on prognosis in the postoperative period for horses with surgical colic.

CT of the intervertebral foramina

The aims of this retrospective, analytical study by Tibor Rovel and co-workers in Belgium were to describe a protocol for quantifying computed tomographic (CT) cervicothoracic intervertebral foramina (IF) size; evaluate the repeatability of IF size measures; test associations between IF size and adjacent articular process (AP) size, ventral extent, and anatomic location; and determine the proportion of IF with narrowing.

Computed tomographic images were acquired in 20 Warmblood horses that presented with forelimb lameness and/or neck pain. All IF between C5 and T2 (n = 160) were evaluated. IF cross-sectional area (CSA), APCSA and AP ventral extent were measured. The repeatability of IFCSA measurement was calculated. Possible associations between IFCSA and APCSA, ventral extent, side or location were assessed. IF narrowing was defined as more than 50% of reduction in IF height when compared to its widest part (s).

The repeatability of IFCSA measurement was excellent. There was a significant association between IFCSA and APCSA, ventral extent and location (higher values between C7 and T2). The association between IFCSA and ventral extent was small. Narrowing was identified in 61 (38.1%) IF. Maximum degree of narrowing was most common at the cranial (26.3%) and middle (68.8%) third of the IF. Narrowing was not identified at T1-T2. The authors concluded that CT cervicothoracic IF size can be measured with excellent repeatability, and associations were found between IF size and AP size, ventral extent and location.

S. WRIGHT
EVE Editorial Office

References

Colombino, E., Raspa, F., Perotti, M., Bergero, D., Vervuert, I., Valle, E. et al. (2022) Gut health of horses: effects of high fibre vs high starch diet on histological and morphometrical parameters. *BMC Veterinary Research*, **18**, 338. https://doi.org/10.1186/s12917-022-03433-y

Dosi, M.C.M.C., McGorum, B.C., Kirton, R.D., Cillán-García, E., Mellanby, R.J., Keen, J.A. et al. (2022) The effect of season, management and endocrinopathies on vitamin D status in horses. *Equine Veterinary Journal*. Epub ahead of print. https://doi.org/10.1111/evj.13873

Quéré, E. & Chahory, S. (2022) Outcomes and complications associated with superior and inferior subpalpebral lavage treatment systems placed in 61 equine eyes (2004-2021). *Journal of Equine Veterinary Science*, **117**, 104076. https://doi.org/10.1016/j.jevs.2022.104076

Rovel, T., Duchateau, L., Saunders, J., Vandenberghe, F. & Vanderperren, K. (2022) CT measures of osseous cervicothoracic intervertebral foramina are repeatable and associated with CT measures of adjacent articular processes in horses. *Veterinary Radiology & Ultrasound*. Epub ahead of print. https://doi.org/10.1111/vru.13158

Smanik, L.E., Moser, D.K., Rothers, K.P. & Hackett, E.S. (2022) Serial venous lactate measurement following gastrointestinal surgery in horses. *Journal of Veterinary Science*, **23**. Epub ahead of print. https://doi.org/10.4142/jvs.22038

Whitlock, F., Grewar, J. & Newton, R. (2022) An epidemiological overview of the equine influenza epidemic in Great Britain during 2019. *Equine Veterinary Journal*. Epub ahead of print. https://beva.onlinelibrary.wiley.com/doi/10.1111/evj.13874

EQUINE VETERINARY EDUCATION
Equine vet. Educ. (2022) **34** (12) 620
doi: 10.1111/eve.13623_1

Case Report

Conservative treatment of an incomplete calcaneal fracture in a pony using a tarsal sleeve cast

M. Marcatili*, ***F. Cantatore***, ***G. Riley and J. Withers***

Crown Inn Farm, Pool House Equine Clinic, Lichfield, UK
**Corresponding author email: marco.marcatili86@gmail.com*

Keywords: horse; calcaneal fracture; sleeve cast

Summary

A 9-year-old 390-kg games pony presented with acute onset of grade 5/5 (AAEP) right hindlimb (RH) lameness. During the clinical examination, the source of lameness was localised to the tarsal region. Radiographical examination identified a closed, simple, non-displaced, incomplete fracture of the calcaneal shaft. The pony was initially treated with box rest and oral phenylbutazone (2.2 mg/kg bwt s.i.d.). Despite an initial good response, the horse re-presented with a grade 5/5 (AAEP) RH lameness, 2 weeks after initial presentation. The decision was made to treat the fracture using a tarsal sleeve cast extending from the mid-third of the tibia/crus to the level of distal metatarsus. The cast was replaced every 2 weeks and maintained for a total of 8 weeks. After cast removal, the horse was kept on strict box rest for 3 weeks. After discharge from the hospital, in-hand walking exercise from the stable was commenced and gradually increased over a 4-week period. The horse was then gradually reintroduced to a small paddock turnout exercise for eight further weeks. The horse was able to return to full athletic function. Conservative treatment using a tarsal sleeve cast should be considered only in horses presenting with an incomplete non-displaced fracture of the calcaneal shaft (**Figs 1** and **2**).

Fig 1: DLPMO radiographic projection of the right tarsus showing the fracture line at presentation (arrow).

Fig 2: DLPMO radiographic projection of the right tarsus taken 12 weeks after discharge from the hospital. Note the radiographic healing of the fracture and resolution of the osteopenia.

Key points

- Incomplete non-displaced fractures of the calcaneal shaft that do not respond to stall rest can be treated with a tarsal sleeve cast.
- The use of a tarsal sleeve cast avoids the need for general anaesthesia, improves the horse's comfort and reduces the risk of complications associated with full limb casts.
- After successful treatment, horses can resume their previous level of activity.


ECHO IQ
WIRELESS
ULTRASOUND
COMPATIBLE
HIGH DEFINITION
WATER-RESISTANT
LONG BATTERY LIFE
LIGHTWEIGHT
MULTIPLE INTERCHANGABLE PROBES HEADS
IMAGE ANYWHERE
VETEL
800-458-8890
www.veteldiagnostics.com

ADVERTISEMENT

RESEARCH UPDATE SPONSORED BY KENTUCKY PERFORMANCE PRODUCTS

Equine Metabolic Syndrome/Insulin Dysregulation: Don't Forget About Protein

by Jane Manfredi, DVM, MS, PhD, DACVS-LA, DACVSMR (Equine)
Assistant Professor, Michigan State University College of Veterinary Medicine

When we think about ideal diets for horses with equine metabolic syndrome (EMS) and/or insulin dysregulation (ID), the first things that come to mind for many are to avoid grain and to minimize the nonstructural carbohydrate (NSC) content in the food.

Current recommendations suggest that NSC should be kept at <10-12% to avoid triggering an insulin spike that could lead to a bout of laminitis.[1] To maintain a low NSC and yet allow the diet to have appropriate amounts of vitamins and minerals, owners often opt to feed a ration balancer vs. traditional grain.

This small volume of pellets can be fed at an NSC of less than 12% and is often recommended by veterinarians to supplement primarily hay diets.

Lowering insulin blood concentrations at rest and after meals is a goal to minimize laminitis risk, and owners are rightly frustrated when they don't see improvements. "I'm soaking the hay, they aren't on grain except for a ration balancer, they live on a dry lot, they are getting appropriate exercise, but I just can't seem to budge the baseline or oral sugar test insulin concentrations" are common refrains in these instances.

While this issue could be related to the horse's pituitary pars intermedia (PPID) status, the amount and type of exercise they are getting, the actual tested NSC content of the hay, and the presence of other chronic illnesses, another possible cause of the persistently high insulin levels that has been overlooked until as of late is the ration balancer's protein content.

While not as important as overall NSC content in triggering insulin responses (Macon et al., 2022[2]), recent work has shown that ration balancers with protein concentrations of above 30% can themselves cause insulin spikes (Loos et al., 2019[3]).

In fact, EMS horses fed a ration balancer with 31% protein had a "9-fold greater insulinemic response" as compared to healthy control horses.

As some ration balancers are produced with protein in the 15% range, for EMS/ID horses that are having issues improving insulin regulation, a change to the lower protein ration balancer may be part of the solution to improving metabolic health.

REFERENCES:

1. https://sites.tufts.edu/equineendogroup/files/2020/09/200592_EMS_Recommendations_Bro-FINAL.pdf, accessed 8/15/22

2. Macon, E. L., Harris, P., Bailey, S., Barker, V. D., & Adams, A. (2022). Postprandial insulin responses to various feedstuffs differ in insulin dysregulated horses compared with non-insulin dysregulated controls. Equine Veterinary Journal, 54(3), 574–583. https://doi.org/10.1111/EVJ.13474

3. Loos, C. M. M., Dorsch, S. C., Elzinga, S. E., Brewster-Barnes, T., Vanzant, E. S., Adams, A. A., & Urschel, K. L. (2019). A high protein meal affects plasma insulin concentrations and amino acid metabolism in horses with equine metabolic syndrome. The Veterinary Journal, 251, 105341.

Equine vet. Educ. (2022) **34** (12) 621
doi: 10.1111/eve.13612_1

Case Report

Haemoperitoneum associated with bilateral granulosa cell tumours in a pregnant mare treated by standing ovariectomy

***M. Sinovich*[†,*], *D. C. Archer*[†], *J. Kane-Smyth*[†], *S. Scarabelli*[†], *A. Ritchie*[‡] *and P. G. Kelly*[§]**

[†]The Philip Leverhulme Equine Hospital, University of Liverpool, Neston; [‡]Alan Ritchie Equine Veterinary Dentistry, Kingsley; and [§]The Royal (Dick) School of Veterinary Studies, University of Edinburgh, Easter Bush, UK
**Corresponding author email: mattsinovich@yahoo.co.uk*

Keywords: horse; GCT; haemoperitoneum; ovariectomy; pregnancy

Summary

An 8-year-old 450-kg Warmblood pony mare, 60 days in foal, was presented for investigation of low-grade colic of 24-hours duration. On rectal examination, the left ovary was enlarged and painful. Rectal ultrasonography showed an abnormal, 7-cm-diameter, well-circumscribed, encapsulated structure with a reticular pattern within the left ovary (**Fig 1**). A unilateral ovarian haematoma was suspected. Repeat ultrasound 72 h later revealed an increase in size (9 cm diameter). Transcutaneous ultrasonographic examination of the abdomen revealed swirling, mixed echogenicity fluid (6–7 cm), compatible with haemoperitoneum (HP) and confirmed by abdominocentesis (PCV 28 %, TP 68 g/L, lactate 2.4 mmol/L). Transrectal ultrasonographic examination 6 days after admission revealed the right ovary had developed a similar lesion. Conservative management was advised, and the mare was discharged 9 days after admission. Within 24 h, the mare represented with acute tachycardia (90 beats/min), pale mucous membranes and increased capillary refill time (>3 seconds). Ultrasonographic examination revealed significant intra-abdominal bleeding. Tranexamic acid (5 mg/kg bwt i.v. once, Cyklokapron) and flunixin meglumine (1.1 mg/kg bwt i.v once, Flunixin) were administered. Haematology revealed a decrease in PCV (24%), severe hypoproteinaemia (TP 36 g/L) and elevated systemic lactate concentration (2.3 mmol/L), consistent with acute haemorrhage. Over the following 12 h, the tachycardia worsened (100 beats/min), and PCV decreased (11%) with hypoproteinaemia (TP 30 g/L). Systemic hyperlactataemia (17.6 mmol/L) and profound hypoxaemia developed (25.5 mmHg despite oxygen supplementation), and she developed an intermittent cough. Haemodynamic supportive therapy was implemented, and the mare underwent a standing bilateral laparoscopic-assisted ovariectomy. Both ovaries were removed through an extended left-sided incision. The ovaries were enlarged (approximately 20 × 25 cm) with hyperaemic and irregular marginated surfaces with tearing of the serosa (**Fig 2**). The mare received further haemodynamic supplementation (whole blood, plasma, colloids and hypertonic saline) in the postoperative period. Minor self-limiting complications occurred (incisional oedema) and the HP resolved. Histopathology of the ovaries confirmed bilateral granulosa theca cell tumours. The surgical sites healed with no complication. At 335 days, the mare delivered a healthy filly foal. Parturition was unassisted and normal.

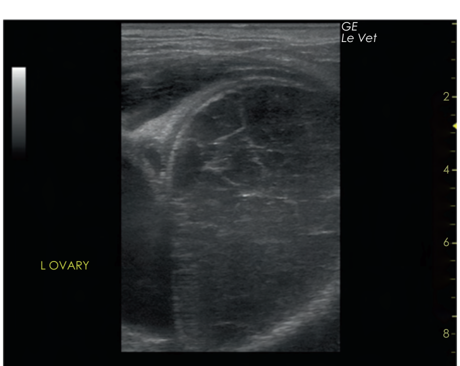


***Fig 1:** Transrectal ultrasonographic image of the left ovary at initial presentation showing the reticulated appearance of the associated suspected haematoma measuring approximately 7 cm.*

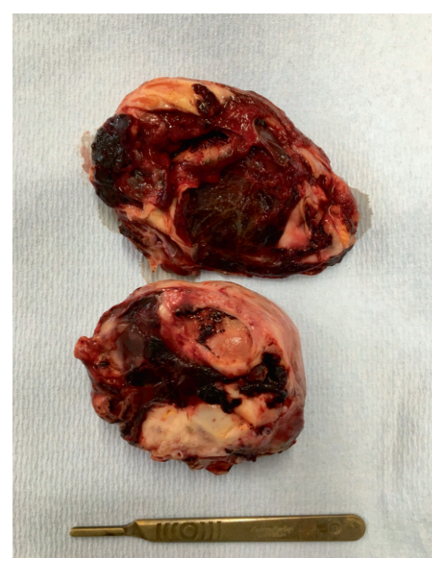


***Fig 2:** Right ovary on cut section after surgical removal showing large regions of coagulated blood and bruising through the capsule.*

Key points

- Granulosa cell tumours should be considered a rare but possible case of haemoperitoneum in mares and ultrasonographic evaluation of the ovaries should be undertaken.
- Granulosa cell tumours (bilateral) can develop in pregnant mares.
- Bilateral ovariectomy in a pregnant mare after 70 days of gestation can result in successful delivery of a live foal.

EQUINE VETERINARY EDUCATION
Equine vet. Educ. (2022) **34** (12) 622-625
doi: 10.1111/eve.13629

Clinical Commentary

Ancillary treatment to support pregnancy in cases of medical disease

T. M. Beachler

Veterinary Diagnostic and Production Animal Medicine, Iowa State University, Ames, Iowa, USA
Corresponding author email: beachler@iastate.edu

Keywords: horse; pregnancy; abortion; maternal disease; progestin

Introduction

Systemic disease occurring in the pregnant mare presents many unique challenges and complications to routine case management, including the limitations on surgical interventions and pharmaceutical choices, as well as the inherent need to support fetoplacental health to prevent pregnancy loss. The Case Report by Sinovich and colleagues in this issue exemplifies some of these challenges (Sinovich et al., 2022). Cases of maternal medical disease affecting almost all body systems can have profound effects on fetoplacental health, fetal viability and pregnancy maintenance due to the presence of severe stress, endotoxaemia or endogenous prostaglandin production (Giles et al., 1993; Perkins, 1999; Bucca, 2006). Therefore, treatment and expedited resolution of the primary disease process when possible is paramount. Due to the varied nature of diseases affecting the vast number of possible body systems, an investigation into individualised pregnancy support measures is impractical, and treatments used in cases of reproductive disease such as ascending placentitis are frequently applied as ancillary measures to support fetoplacental health and to promote pregnancy maintenance.

Progestins

Progestins are the clinical first-line defence to assist the maintenance of pregnancy in cases of maternal medical disease. While progestins have been used to promote uterine quiescence in horses for the last 30 years, most of the evidence supporting their use in preventing pregnancy loss was documented in the early stages of pregnancy. Altrenogest, a synthetic oral progestin, was shown to prevent pregnancy loss in 100% of mares treated with the synthetic prostaglandin, cloprostenol, while all cloprostenol only treated control mares aborted (Daels et al., 1996). Additionally, in a model of experimental endotoxaemia, mares between 21 and 35 days of gestation, who were administered 44 mg of daily altrenogest in the face of systemic endotoxin to stimulate endogenous prostaglandin production and pregnancy loss, were able to remain pregnant until Day 70 of gestation (Daels et al., 1991a). Therefore, these studies, and the study by Bailey and co-workers (2010) demonstrating improved outcomes when altrenogest was used as multimodal therapy in experimental placentitis, have supported altrenogest use in any mare at risk for abortion or experiencing systemic illness in mid-to-late pregnancy.

The standard labelled or 'single' dose of altrenogest for suppressing oestrus is 0.044 mg/kg bwt per os q. 24 h. In cases of severe maternal disease, most practitioners initiate a 'double dose' of 0.088 mg/kg bwt per os q. 24 h as used in the study by Daels et al. (1996). The length of treatment required varies on a case-by-case basis. Many practitioners administer a double dose of altrenogest before decreasing to a single dose in mid- to late-term pregnant mares whose medical disease has resolved and in which the pregnancy appears stable (Lu, 2012). Injectable altrenogest and long-acting progesterone in oil (1500 mg i.m. q. 7-14 days) formulations are also available that may be administered intramuscularly on a weekly to biweekly basis, providing an avenue of administration in mares who are unable to receive oral medications whether due to administrator preference, mare cooperation or concurrent maternal disease (McKinnon et al., 2000; Vanderwall et al., 2007). A recent study also examined the pharmacokinetics of rectally administered altrenogest and found that due to rectal bioavailability, administration of 0.088 mg/kg bwt every 4–8 h would be required to reach acceptable therapeutic levels (Ellis et al., 2019).

The question of whether and when to discontinue progestin therapy remains a challenging discussion amongst practitioners and owners alike. In the face of continued systemic or reproductive insult, progestin therapy is often continued until parturition. In cases of elective administration, or cases of maternal medical disease, many practitioners recommend performing a gradual taper of the amount administered over the course of at least 10–14 days to allow the endogenous endocrine system to adapt; however, no studies have shown a direct adverse effect to sudden progestin drop (Kelleman, 2013; Perkins, 1999). As altrenogest does not cross-react with progesterone assays, endogenous progesterone or total progestogen concentration, depending on the stage of gestation, may be assessed on routine progesterone assays prior to discontinuation (Jackson et al., 1986). This is contrary to injectable progesterone formulations, as both endogenous and exogenous progesterone would be detected on assay analysis, limiting its usefulness. Timing of a gradual taper may be performed after confirmation of acceptable endogenous progesterone levels in stable pregnancies as discussed above, after the fetoplacental unit becomes functional at 100–120 days of gestation, or at approximately 320 days of gestation due to possible side effects of chronic administration (Conley & Ball, 2019; Kelleman, 2013; Lu, 2012). Mares treated with altrenogest after 280 days of gestation until foaling displayed prolonged stage II of parturition, and foals exhibited lower respiratory rates, higher blood pH, altered neutrophil to lymphocyte ratio and possible increased need for advanced supportive care (Neuhauser et al., 2008, 2009). Finally, enlarged clitoral size has been noted in fillies born to mares treated throughout pregnancy from 20 to 325 days of gestation (Shoemaker et al., 1989).

Anti-inflammatories

Nonsteroidal anti-inflammatories are commonly used to assist in pregnancy maintenance in addition to their use as therapy for many underlying primary disease processes. Anti-inflammatory therapy aims at reducing and halting the pro-inflammatory response and production of inflammatory cytokines and prostaglandins, as each has been implicated in preterm labour and abortion in horses as well as a multitude of other species (LeBlanc et al., 2012). Anti-inflammatory therapy may also serve as an anti-endotoxic agent or analgesic in appropriate cases. Common nonsteroidals used include flunixin meglumine (1.1 mg/kg bwt i.v. or per os q. 12 h) or phenylbutazone (2.2 mg/kg bwt i.v. or per os q. 12 h). Supporting administration in cases of maternal medical disease, the nonsteroidal cyclo-oxygenase inhibitor flunixin meglumine has been shown in early gestation to maintain progesterone levels and promote pregnancy maintenance in an experimental model of endotoxaemia (Daels et al., 1991a, b). When flunixin meglumine was administered to mares between 21 and 44 days of gestation before endotoxin administration, all mares (7/7) maintained pregnancy. When administered following endotoxin administration, systemic progesterone declined, and pregnancy was lost in 1/3 mares at one hour and 3/3 mares at two hours respectively (Daels et al., 1991b).

Recently, the primarily COX-2-selective anti-inflammatory firocoxib has been investigated in the pregnant mare (Giguère et al., 2016; Macpherson et al., 2021) as firocoxib ideally has less deleterious effects on the gastrointestinal and renal systems. Initial work illustrated no adverse effects in mares treated with daily oral firocoxib at 0.1 mg/kg bwt, but the maximum concentration of the drug was significantly lower in pregnant mares (Giguère et al., 2016). As firocoxib has a long half-life, the authors proposed that a steady state in pregnant mares could be reached by using a loading dose of 0.3 mg/kg bwt followed by 0.1 mg/kg bwt by mouth every 24 h akin to the practice performed in other musculoskeletal and gastrointestinal conditions in the horse (Cox et al., 2013; Giguère et al., 2016). Macpherson and colleagues (2021) followed this work by using the loading dose of 0.3 mg/kg bwt per os q. 24 h, followed by 0.1 mg/kg bwt per os q. 24 h in an experimental model of ascending placentitis. Compared with untreated infected animals, mares who received firocoxib demonstrated reduced concentrations of multiple inflammatory cytokines and prostaglandins within the allantoic fluid (Macpherson et al., 2021). Therefore, firocoxib may serve as a beneficial therapeutic in mares requiring prolonged anti-inflammatory therapy for the treatment of their primary disease process.

Pentoxifylline is an immune modulator that is believed to have multifactorial actions, including preventing the release of inflammatory cytokines, enhancing uterine blood flow and diminishing bacterial adhesion (Heller et al., 1999; Lauterbach & Zemballa, 1996; Ousey et al., 2010). However, a recent study by Bailey and colleagues was unable to detect any improvement in uterine arterial blood flow through Doppler ultrasonography in pregnant mares when treated with pentoxifylline at 17 mg/kg bwt per os q. 24 h daily (Bailey et al., 2012). Regardless of the mechanism of action, in a separate efficacy study, an improved pregnancy outcome occurred in an experimental model of placentitis, when combination therapy of pentoxifylline was used in conjunction with trimethoprim–sulfamethoxazole and altrenogest (Bailey et al., 2010). Therefore, pentoxifylline continues to be used in many cases of ascending placentitis and may serve a similar purpose in cases of maternal medical disease.

Finally, acetylsalicylic acid or aspirin is another anti-inflammatory agent (50 mg/kg bwt per os q. 12 h) that is clinically gaining favour with some practitioners for use in pregnancy maintenance. In women, acetylsalicylic acid is known to inhibit platelet aggregation, thereby increasing blood flow, and is used to prevent pregnancy-induced hypertension, pre-eclampsia and intrauterine growth restriction (Meher et al., 2017; Sibai et al., 1989; Vainio et al., 2002). Akin to pentoxifylline, recent investigations have examined its effects as a rheostatic agent via Doppler ultrasonography and found that in late pregnancy, the total arterial blood flow was significantly higher in mares receiving acetylsalicylic acid compared with controls (Sielhorst et al., 2018). Its use has also been investigated in a single efficacy study, where Christiansen and co-workers (2010) administered acetylsalicylic acid, trimethoprim–sulfamethoxazole and altrenogest in an experimental model of ascending placentitis and produced 9 out of 12 viable foals in treated mares.

Tocolytics

The use of tocolytics such as β-sympathomimetics, calcium channel blockers, prostaglandin synthesis inhibitors and magnesium sulphate to suppress uterine contractions are a crucial part of multimodal therapy to treat preterm labour in women (Rundell & Panchal, 2017). In pregnant mares, limited research has been performed with varied results. To date, the β-sympathomimetic clenbuterol has received the most attention. Card and Wood (1995) first illustrated that administration of 300 μg of intravenous clenbuterol at varied gestational stages decreased appreciated transrectal uterine tone for up to 120 min alongside maternal and fetal heart rate elevations. However, when administered at multiple dosages prior to foaling in another study, clenbuterol could not prolong natural parturition and potentially even caused treated mares to foal earlier than untreated controls (Palmer et al., 2002). This contrary effect was hypothesised to be due to cervical dilation following relaxation of the cervical smooth musculature that may have resulted in a hastening of parturition. Therefore, due to the varied and possible detrimental results against pregnancy maintenance, tocolytic use remains limited in the clinical setting.

Nutrition

Nutritional support is as a critical part of supporting a pregnant mare and addressing the primary disease process (Dolente, 2004). Nutritional requirements of the pregnant broodmare increase dramatically during late gestation, where mares require up to 1.3–1.5 times the adult maintenance requirements for energy and protein (National Research Council, 2007; Robles et al., 2021). Additionally, in a study by Silver and colleagues, experimental fasting in the pregnant mare was shown to increase the concentration of a prostaglandin metabolite along with possible premature delivery (Silver, 1982). Nutritional supplementation, therefore, may need to be considered in cases that require prolonged fasting either via parental nutrition or intravenous dextrose administration (Dolente, 2004).

Acupuncture and acupressure

Acupuncture is gaining interest amongst veterinary clinicians and owners alike for its potential to serve as adjunctive therapy for pregnancy maintenance. While to date, no controlled studies have been performed in pregnant mares, the use of both acupuncture and acupressure has been investigated as methods to both stimulate and inhibit labour in women in addition to its use as a source of nonpharmaceutical analgesia during parturition (Gentz, 2001; Tseui et al., 1977). In pregnant rats, a study by Pak et al. (2000) illustrated significant suppression of oxytocin-induced uterine contractions following stimulation of the acupoint LI-4. While specific studies have not shown a direct link between its performance and iatrogenic abortion, due to the duality of possible points to cause both the induction of labour and promotion of uterine quiescence, caution is recommended with its performance only by experienced and trained practitioners (Schofield, 2008; Shmalberg & Xie, 2011).

Conclusions

In conclusion, multiple ancillary measures may be initiated to support gestational health in cases of maternal medical disease. Regardless of the ongoing disease process and supportive measures elected, frequent assessment of fetoplacental health should be performed to assess response to treatment and prevent maintenance of a nonviable pregnancy.

Acknowledgement

Open access funding provided by the Iowa State University Library. [Correction added on 24 May 2022, after first online publication: ISUL funding statement has been added.]

Conflicts of interest

No conflicts of interest to declare.

Ethical animal research

Ethical animal research was not applicable to this clinical commentary.

References

Bailey, C.S., Macpherson, M.L., Pozor, M.A., Troedsson, M.H., Benson, S., Giguère, S. et al. (2010) Treatment efficacy of trimethoprim sulfamethoxazole, pentoxifylline and altrenogest in experimentally induced equine placentitis. *Theriogenology*, **74**(**3**), 402–412.

Bailey, C.S., Sper, R.B., Schewmaker, J.L., Buchanan, C.N., Beachler, T.M., Pozor, M.A. et al. (2012) Uterine artery blood flow remains unchanged in pregnant mares in response to short-term administration of pentoxifylline. *Theriogenology*, **77**(**2**), 430–436.

Bucca, S. (2006) Diagnosis of the compromised equine pregnancy. *The Veterinary Clinics of North America. Equine Practice*, **22**, 749–761.

Card, C.E. & Wood, M.R. (1995) Effects of acute administration of clenbuterol on uterine tone and equine fetal and maternal heart rates. *Biology of Reproduction*, **Monograph_1**, 7–11.

Christiansen, D.L., Moulton, K., Hopper, R.M., Walters, F.K., Cooley, A.J., LeBlanc, M.M. et al. (2010) Evidence-based medicine approach to develop efficacious therapies for late-gestation mares presenting with uterine infections using an experimentally-induced placentitis model. *Animal Reproduction Science*, **121S**(**1–2**), S345–S346.

Conley, A. & Ball, B.A. (2019) Steroids in the establishment and maintenance of pregnancy and parturition in the mare. *Reproduction*, **158**(**6**), R197–R208.

Cox, S., Villarino, N., Sommardahl, C., Kvaternick, V., Zarabadipour, C., Siger, L. et al. (2013) Disposition of firocoxib in equine plasma after an oral loading dose and a multiple dose regimen. *The Veterinary Journal*, **198**(**2**), 382–385.

Daels, P.F., Besognet, B., Hansen, B., Mohammed, H., Odensvik, K. & Kindahl, H. (1996) Effect of progesterone on prostaglandin F2 alpha secretion and outcome of pregnancy during cloprostenol-induced abortion in mares. *American Journal of Veterinary Research*, **57**(**9**), 1331–1337.

Daels, P.F., Stabenfeldt, G.H., Hughes, J.P., Odensvik, K. & Kindahl, H. (1991a) Evaluation of progesterone deficiency as a cause of fetal death in mares with experimentally induced endotoxemia. *American Journal of Veterinary Research*, **52**(**2**), 282–288.

Daels, P.F., Stabenfeldt, G.H., Hughes, J.P., Odensvik, K. & Kindahl, H. (1991b) Effects of flunixin meglumine on endotoxin-induced prostaglandin F2 alpha secretion during early pregnancy in mares. *American Journal of Veterinary Research*, **52**(**2**), 276–281.

Dolente, B.A. (2004) Critical peripartum disease in the mare. *The Veterinary Clinics of North America. Equine Practice*, **20**(**1**), 151–165.

Ellis, K.E., Council-Troche, R.M., Von Dollen, K.A., Beachler, T.M., Bailey, C.S., Davis, J.L. et al. (2019) Pharmacokinetics of intrarectal altrenogest. *Journal of Equine Veterinary Science*, **72**, 41–46.

Gentz, B.A. (2001) Alternative therapies for the management of pain in labor and delivery. *Clinical Obstetrics and Gynecology*, **44**(**4**), 704–732.

Giguère, S., Macpherson, M.L., Benson, S.M., Cox, S., McNaughten, J.W. & Pozor, M.A. (2016) Disposition of firocoxib in late pregnant and early postpartum mares. *Journal of Veterinary Pharmacology and Therapeutics*, **39**(**2**), 196–198.

Giles, R.C., Donahue, J.M., Hong, C.B., Tuttle, P.A., Petrites-Murphy, M.B., Poonacha, K.B. et al. (1993) Causes of abortion, stillbirth, and perinatal death in horses: 3,527 cases (1986–1991). *Journal of the American Veterinary Medical Association*, **203**(**8**), 1170–1175.

Heller, S., Weber, K., Heller, A., Urbaschek, R. & Koch, T. (1999) Pentoxifylline improves bacterial clearance during hemorrhage and endotoxemia. *Critical Care Medicine*, **27**(**4**), 756–763.

Jackson, S.A., Squires, E.L. & Nett, T.M. (1986) The effect of exogenous progestins on endogenous progesterone secretion in pregnant mares. *Theriogenology*, **25**(**2**), 275–279.

Kelleman, A.A. (2013) Equine pregnancy and clinical applied physiology. *Proceedings of the American Association of Equine Practice*, **59**, 350–358.

Lauterbach, R. & Zembala, M. (1996) Pentoxifylline reduces plasma tumor necrosis factor-alpha in premature infants with sepsis. *European Journal of Pediatrics*, **155**(**5**), 404–409.

LeBlanc, M.M., Giguère, S., Lester, G.D., Brauer, K. & Paccamonti, D.L. (2012) Relationship between infection, inflammation, and premature parturition in mares with experimentally induced placentitis. *Equine Veterinary Journal* **44**(**Suppl. 41**), 8–14.

Lu, K. (2012) How to maintain pregnancy. *Proceedings of the American Association of Equine Practice*, **58**, 334–338.

Macpherson, M.L., Giguère, S., Pozor, M.A., Burden, C.A., Berghaus, L.J., Berghaus, R.D. et al. (2021) Evidence for anti-inflammatory effects of firocoxib administered to mares with experimentally induced placentitis. *American Journal of Reproductive Immunology*, **86**, e13396. https://doi.org/10.1111/aji.13396.

McKinnon, A.O., Lescun, T.B., Walker, J.H., Vasey, J.R. & Allen, W.R. (2000) The inability of some synthetic progestogens to maintain pregnancy in the mare. *Equine Veterinary Journal*, **32**, 83–85.

Meher, S., Duley, L., Hunter, K. & Aksie, L. (2017) Antiplatelet therapy before and after 16 weeks gestation for preventing preeclampsia: an individual participant data metanalysis. *AJOG*, **216**(**2**), 121–128.

National Research Council (2007) *In: Nutrient Requirements of Horses*, 6th edition. Washington, D.C.: The National Academies Press.

Neuhauser, S., Palm, F., Ambuehl, F. & Aurich, C. (2008) Effects of altrenogest treatment of mares in late pregnancy on parturition and on neonatal viability of their foals. *Experimental and Clinical Endocrinology & Diabetes*, **116**(**7**), 423–428.

Neuhauser, S., Palm, F., Ambuehl, F., Mostl, E., Schwendenwein, I. & Aurich, C. (2009) Effect of altrenogest-treatment of mares in late gestation on adrenocortical function, blood count and plasma electrolytes in their foals. *Equine Veterinary Journal*, **41**(**6**), 572–577.

Ousey, J.C., Koelling, M., Willis, D. & Allen, W.R. (2010) Effects of pentoxifylline on uterine blood flow, and placental and fetal development in young and aged mares with endometriosis. *Animal Reproduction Science*, **121**, 343–344.

Pak, S.C., Na, C.S., Kim, J.S., Chae, W.S., Kamiya, S., Wakatsuki, D. et al. (2000) The effect of acupuncture on uterine contraction induced by oxytocin. *American Journal of Chinese Medicine*, **28**(**1**), 35–40.

Palmer, E., Chavatte-Palmer, P., Duchamp, G. & Levy, I. (2002) Lack of clenbuterol for delaying parturition in late pregnant mares. *Theriogenology*, **58**(**2**), 797–799.

Perkins, N. (1999) Equine reproductive pharmacology. *The Veterinary Clinics of North America. Equine Practice*, **15**(**3**), 687–704.

Robles, M., Hammer, C., Staniar, B. & Chavatte-Palmer, P. (2021) Nutrition of broodmares. *The Veterinary Clinics of North America. Equine Practice*, **37**, 177–205.

Rundell, K. & Panchal, B. (2017) Preterm labor: prevention and management. *American Family Physician*, **95**(**6**), 366–372.

Schofield, W.A. (2008) Use of acupuncture in equine reproduction. *Theriogenology*, **70**(**3**), 430–434.

Shmalberg, J. & Xie, H. (2011) Acupuncture and Chinese herbal medicine for treating horses. *Compendium on Continuing Education for the Practicing Veterinarian*, **33**(**5**), E1–E11.

Shoemaker, C.F., Squires, E.L. & Shideler, R.K. (1989) Safety of altrenogest in pregnant mares and on health and development of offspring. *Journal of Equine Veterinary Science*, **9**, 69–72.

Sibai, B.M., Mirro, R., Chesney, C.M. & Leffler, C. (1989) Low-dose aspirin in pregnancy. *Journal of Obstetrics and Gynaecology*, **74**(**4**), 551–557.

Sielhorst, J., Bucker, U., Kahler, A., Rohn, K., Koch, R., Pfarrer, C. et al. (2018) Effect of acetylsalicylic acid on uterine blood flow and feto-placental development in pregnant mares. *Journal of Equine Veterinary Science*, **66**, 233.

Silver, M. & Fowden, A.C. (1982) Uterine prostaglandin F metabolite production in relation to glucose availability in late pregnancy and a possible influence of diet on time of delivery in the mare. *Journal of Reproduction and Fertility. Supplement*, **32**, 511–519.

Sinovich, M., Archer, D.C., Kane-Smyth, J., Scarabelli, S., Ritchie, A. & Kelly, P.G. (2022) Haemoperitoneum associated with bilateral granulosa cell tumours in a pregnant mare treated by standing ovariectomy. *Equine Veterinary Education*. **34**, 621, e526-e532.

Tsuei, J.J., Lai, Y. & Sharma, S.D. (1977) The influence of acupuncture stimulation during pregnancy: the induction and inhibition of labor. *Obstetrics and Gynecology*, **50**(**4**), 479–478.

Vainio, M., Kujansuu, E., Iso-mustojarvi, M. & Maenpaa, J. (2002) Low dose acetylsalicylic acid in prevention of pregnancy-induced hypertension and intrauterine dose retardation in women with bilateral uterine artery notches. *BJOG*, **109**(**2**), 161–167.

Vanderwall, D.K., Marquardt, J.L. & Woods, G.L. (2007) Use of a compounded long-acting progesterone formulation for equine pregnancy maintenance. *Journal of Equine Veterinary Science*, **27**(**2**), 62–66.

EQUINE VETERINARY EDUCATION
Equine vet. Educ. (2022) **34** (12) 626-634
doi: 10.1111/eve.13608

Original Article

A detailed radiographic description and correlated magnetic resonance imaging findings of an infrequently identified articular indentation of the articular margin of the distal phalanx

***S. K. Frietman*†,*, *C. D. M. Van Aert*‡, *F. ter Braake*§, *E. Compagnie*§ and *N. De Heer*§**

†Veterinary Clinic Den Ham, Den Ham, The Netherlands; ‡Veterinary Clinic De Lingehoeve, Lienden, The Netherlands; and §Veterinary Clinic Emmeloord, Emmeloord, The Netherlands
**Corresponding author emails: s.frietman@dierenkliniekdenham.nl; katotofrietman@icloud.com*

Keywords: horse; lameness; MRI; OCLL; pre-purchase examination

Summary

Background: Equine veterinarians frequently obtain lateromedial radiographs of the feet. During assessment, one infrequently encounters a triangular-shaped articular indentation of the articular surface of the distal phalanx (P3). To the authors' knowledge, there are no detailed radiographic or MRI descriptions of this specific articular indentation in the literature so far.

Objectives: The main purpose of this study was to give a detailed morphological description of this radiographical identified articular indentation.

Study design: Descriptive study.

Methods: All LM and DP radiographs of the feet of horses presented at our hospital between August 2016 and August 2019 were retrospectively reviewed for presence of an articular indentation. Following selection, patient information, patient history, clinical findings, MRI-finding and surgical details were retrieved. In total, 30 horses were included of which 12 underwent magnetic resonance imaging. Radiographs and MRI results were evaluated for the precise location, shape and extent of the articular indentation and for signs of degenerative joint disease of the DIPJ.

Results: Four different indentation types were identified radiographically. Concomitant low field MRI proved to be a useful and excellent imaging modality for evaluation of this rare articular indentation and its surrounding subchondral bone. MRI findings were various and ranged from slight subchondral contour deviations to obvious OCLL (Osseous Cyst Like Lesions). Furthermore, MRI identified some additional indentation related OCLLs that were not noted on plain radiographs.

Main limitations: The limited number of horses that were included and the absence of complementary histopathology.

Conclusions: Articular indentations are typically identified in the third quarter of the articular margin of P3 and may have underlying OCLLs. Since OCLLs are known to be a potential cause of future unsoundness, careful radiographic assessment is advised if an indentation is encountered. If needed, Standing Low-Field MRI can give additional and detailed information.

Clinical relevance

- This study describes the infrequently encountered triangular-shaped articular indentation of the articular surface of the distal phalanx on the LM view of the foot.
- Articular indentations may communicate with underlying osseous cyst like lesions, therefore careful assessment of both LM and DP views is strongly advised.
- Long-term prognosis still needs to be determined.

Introduction

In equine veterinary practice lateromedial (LM) radiographs of the distal phalanx (P3) are routinely obtained for lameness diagnostics and pre-purchase purposes. Multiple pathological conditions affecting the distal interphalangeal joint (DIPJ) have been described, such as extensor process fragments, sepsis, osteoarthritis and osseous cyst-like lesions (OCLLs) (Butler et al., 2008). OCLLs, also referred to as subchondral cystic lesions or subchondral bone cysts, are common in horses (Fürst et al., 1997; Garcia-Lopez & Kirker-Head, 2004).

Butler et al. (2008) reported the presence of a smoothly outlined V-shaped notch (**Fig 1**) in the middle of the articular margin of P3 on standard LM radiographs that clearly differed from the articular irregularity which is commonly seen with extensor process OCLLs. This specific V-shaped notch, also referred to as an articular indentation, was reported to be a coincidental finding with presumably minimal clinical significance. Recently, Peter et al. (2018) assessed the association of radiographically identified OCLLs of P3 with lameness and racing performance in Thoroughbred racehorses. In some (36%) of these horses, the radiographic identified OCLL was associated with an articular indentation of the distal phalanx. However, since detailed information about the exact location and specific morphology of the articular indentation is lacking, its clinical significance remains unknown.

Osseous cyst-like lesions usually arise in the subchondral bone of the main weight-bearing surface of the joint and may cause future lameness (Baxter, 1996; Dyson et al., 2005; Mair & Sherlock, 2008; McIlwraith, 1990). After the medial femoral

Fig 1: Type 1 articular indentation of the distal phalanx. Red arrow: points out the indentation.

condyle (45.8%), the phalanges (26.2%) are the second most commonly affected (von Rechenberg et al., 1998). Radiographically, OCLLs of the weight-bearing surface of the DIPJ are most easily visualised on dorsopalmar or dorsoproximal–palmarodistal oblique views (Butler et al., 2008; Peter et al., 2018). However, multiple factors impede the radiographic identification of small or early-stage OCLLs. First, bone mineral density must change by approximately 30–50% before osseous lesions become radiologically apparent (Butler et al., 2008; Konde, 1998). Second, significant superposition (as a result of irregular joint contours, anatomic variation and different bone densities) may further complicate correct identification. Finally, the centre of the frog may create a lucency that mimics the presence of an OCLL (Butler et al., 2008; Story & Bramlage, 2004; Trotter & Dyson, 2003; Von Suntum & Hartung, 1989). Therefore, recognition of early stage or small OCLLs remains challenging when radiography alone is used. For subtle and complicated cases, complementary techniques, such as MRI and computed tomography (CT), are warranted (Dyson et al., 2003; Mair & Sherlock, 2008; Schön et al., 2017; Young et al., 2012).

Our purpose was to 1) describe the different shapes and precise location of the infrequent indentation of the articular margin of the DIPJ on plain LM radiographs of the equine foot; 2) to describe correlating MR imaging findings of this specific indentation and 3) to try to elucidate the clinical importance of this rare radiographic finding.

Materials and methods

Study population and study design

For this study, all radiographs of the feet of horses presented at our hospital between August 2016 and August 2019 were retrospectively reviewed. Radiographs were obtained using two different digital radiographic systems, a Konica Minolta Aero DR-system (Scil Animal Care Company BV) and a Fuji-film DR-system (Veterinary Solutions), using standard settings of 70 kV/4 mAs for the LM views and 60 kV/20 mAs for the dorsopalmar views. In total, 1683 LM radiographs of 1041 horses were retrospectively reviewed. Horses were only selected for inclusion if (1) a distinct subchondral indentation of the articular margin of the distal interphalangeal joint (DIPJ) was observed on the LM radiographs (**Fig 1**) and if (2) the radiographs were of sufficient diagnostic quality that allowed accurate measurement taking. Finally, 30 horses met the selection criteria. Images were stored and reviewed in DICOM format.

Following selection, case information, case history, clinical findings, MRI findings (if present) and surgical details were retrieved (**Table 1**). Twelve of the 30 horses underwent magnetic resonance imaging. Magnetic resonance findings of five horses were retrospectively reviewed as MRI was performed as part of the lameness examination. The remaining seven horses underwent a prospective MRI using a specific study-based protocol. Four horses had both feet examined (16 feet scanned in total).

Radiographic assessment

All radiographs were reviewed by one specialist radiologist (N.H.) and one surgical resident (S.F.). Radiographs were evaluated for extent and shape of the articular indentation of the articular surface of P3 and for signs of degenerative joint disease of the DIPJ. Once consensus was reached, radiographic identified indentations were classified into four different types: Type 1: a small or broad, shallow or deep, angulated to curved or triangular articular indentation *without* fragmentation; Type 2: a small or broad, shallow or deep, angulated to curved or triangular articular indentation *with* fragmentation; Type 3: a small or broad, triangular articular indentation with a dorsal, central or palmar/plantar located concomitant subchondral osseous cyst-like lesion; and Type 4: a small or broad, triangular articular indentation with a dorsal, central or palmar/plantar located concomitant subchondral osseous cyst-like lesion articular indentation *with* fragmentation (**Fig 2a-d** and **Table 1**).

Subsequently, the degree of DIPJ osteoarthritis was subjectively assessed and classified into four different categories (**Table 2**). Once all LM radiographs were reviewed, all available and corresponding dorsopalmar/dorsoplantar views were evaluated for presence of any radiolucency potentially related to the articular indentation. Following identification on the dorsopalmar views, the position of the articular indentation in the lateromedial plane was determined.

Next, using the LM view, the exact position of the articular indentation in the sagittal plane was determined. Measurements were taken and processed by one author (S.F.), using a geometric program, Geogebra Classic (GeoGebra GmbH). First, the distance from the extensor process until the articular indentation was measured (Distance 1 (D1)) followed by the total length of the articular margin of P3 (Distance 2 (D2)) (**Fig 3**). Next, the exact location of the articular indentation was calculated using a D1:D2 ratio (**Table 1**).

Magnetic resonance imaging and assessment

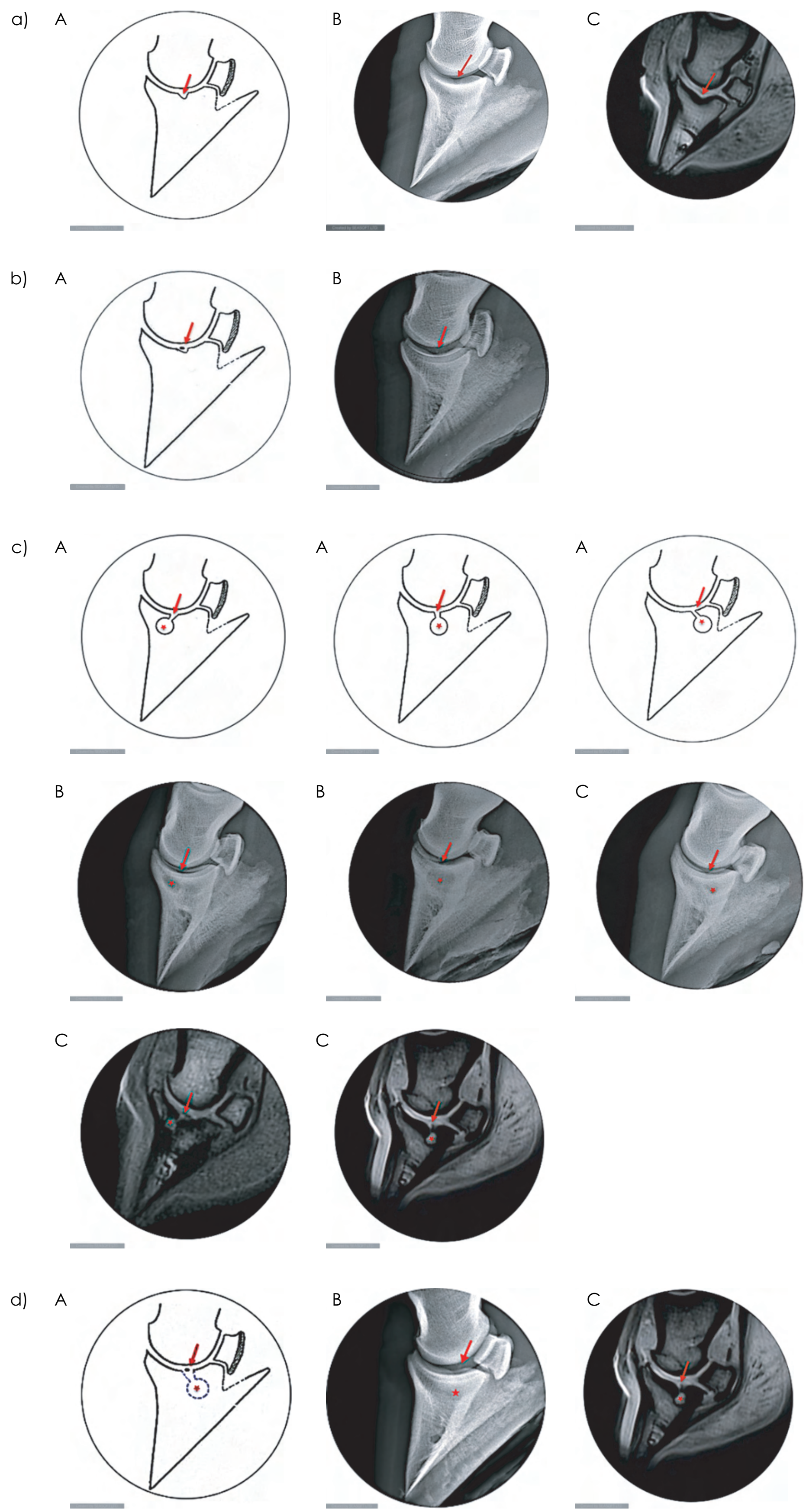
MRI was performed under sedation using a 0.27 Tesla standing MRI unit (Hallmarq Veterinary Imaging) with a dedicated extremity radiofrequency coil. Five horses underwent MRI examination because of unrelated foot

TABLE 1: Clinical, radiographic and MRI findings in 30 horses.

Case No.	Breed	Age	Gender	Limb	Ind. Type	OA grade	D1: D2	DP View	Radiolucency on DP	Lameness	Lameness causes	MRI Performed
1	WB	5 year	Geld	LF	1	None	64%	+	–	No		Yes
				RF	1	None	57%	+	–			No
2	FH	5 year	Stal	LF	1	None	62%	–		Yes	Large Ext. Proc.	No
				RF	1	None	65%	–			Fragment	No
3	FH	11 year	Geld	RF	1	None	74%	+	–	Yes	Large Ext. Proc. Fragment	No
4	HH	17 year	Mare	LF	1	Mild	73%	+	–	No		Yes
5	FH	5 year	Geld	LF	1	None	65%	+	+	Yes	Impar ligament	Yes
				RF	1	None	54%	+	+		desmitis	Yes
6	FH	21 year	Geld	LH	1	Moderate	65%	–		Yes	Hoofcanker	No
				RH	1	Moderate	69%	–				No
7	WB	9 year	Geld	LF	1	None	68%	+	+	Yes	Undefined	No
				RF	1	None	67%	+	+			No
8	FH	15 year	Mare	LF	1	None	76%	+	+	Yes	Type VI P3 Fracture	No
9	WB	3 year	Stal	LF	2	None	62%	+	+	No		No
				RF	1	None	57%	+	+			No
10	FH	11 year	Mare	LF	1	Moderate	76%	+	+	Yes	Type III P3	Yes
				RF	1	None	64%	+	–		Fracture	Yes
11	AH	15 year	Mare	RF	1	Mild	57%	+	+	Yes	Chronic laminitis	No
12	WB	7 year	Mare	LF	1	None	58%	–		No		No
				RF	1	None	59%	–				No
13	WB	2 year	Stal	LF	3	None	56%	+	+	No		No
14	FH	19 year	Mare	LF	1	Mild	63%	+	–	Yes	Undefined	Yes
				RF	1	Mild	61%	+	–			Yes
15	FH	10 year	Mare	LF	1	Mild	62%	–		Yes	Standard Ext.	Yes
				RF	1	Mild	67%	–			Proc. Fragment	Yes
16	WB	14 year	Geld	LF	1	Mild	63%	+	+	Yes	Podotrochlear disease	Yes
17	WB	5 year	Mare	RF	1	None	59%	+	–	No		No
18	WB	18 year	Geld	LF	1	None	70%	+	+	Yes	Keratoma	Yes
19	FH	4 year	Stal	RF	1	None	71%	+	–	Yes	Severe pododermatitis	No
20	WB	2 year	Mare	RF	1	None	73%	+	–	No		No
21	WB	7 year	Stal	LF	3	None	63%	+	+	Yes	Septic tenosynovitis	No
				RF	1	None	63%				carpal sheath	No
22	WB	6 year	Geld	LF	1	None	65%	+	+	No		No
				RF	1	None	64%	+	+			No
23	FH	3 year	Geld	LF	1	None	62%	+	+	Yes	OA RC-joint	No
24	FH	18 year	Stal	LF	1	Severe	65%	+	+	Yes	OA DIPJ-PIPJ	No
				RF	1	Severe	62%	+	+			No
25	WB	2 year	Mare	LF	3	None	57%	+	+	No		Yes
26	FH	1 year	Mare	RF	1	None	66%	+	–	Yes	Large Ext. Proc. Fragment	Yes
27	WB	4 year	Mare	LF	4	None	64%	+	+	No		Yes
28	WB	5 year	Geld	LF	1	None	76%	+	–	No		Yes
				RF	4	None	73%	+	+			Yes
29	WB	3 year	Stal	LF	3	None	72%	+	+	No		No
30	WB	3 year	Geld	LF	3	None	75%	+	+	No		No
				RF	3	None	56%	+	+			No

AH, Appaloosa horse; Bil, Bilateral; FH, Friesian horse; HH, Haflinger horse; Ind.P2, Indentation distal P2, + = present, - = absent; OA signs, Osteoarthritis signs; Uni, Unilateral; WB, Warmblood horse.

***Fig 2:** (a) Type 1. Schematic image (A), lateromedial radiograph (B) and sagittal T2* MRI image (C) of the DIP joint, showing a Type 1 articular indentation of the distal phalanx. Red Arrow: points out the articular indentation. (b) Type 2 - Case Nr. 9 – No MRI performed. Schematic image (A), lateromedial radiograph (B) of the DIP joint showing a Type 2 articular indentation of the distal phalanx. Red Arrow: points out the articular indentation + fragment. (c) Type 3 - Dorsal, Middle and Palmar located OCLL. Schematic images (A), lateromedial radiographs (B) and sagittal T2* MRI images (C) of the DIP joint, showing a Type 3 indentation of the distal phalanx with concomitant OCLL (dorsal, middle and palmar). Red Arrow: points out the indentation, Red Asterisk: points out the OCLL. (d) Type 4. Schematic image (A), lateromedial radiograph (B) and Sagittal T2* MRI image (C) of the DIP joint showing a Type 4 indentation of the distal phalanx. Red Arrow: points out the articular indentation + fragment, Red Asterisk: points out the OCLL.*


a) A
B
C
b) A
B
c) A
A
A
B
B
C
C
C
d) A
B
C

pathology using our standard clinical protocol. This protocol consisted of a T2*W sagittal, T2*W transverse in a right angle to the deep digital flexor tendon (DDFT) proximal to the navicular bone, STIR sagittal, T2*W frontal on a right angle to the distal DDFT, T2W FSE transverse parallel to the floor, STIR transverse parallel to the floor, T2W FSE frontal parallel to the axis of the foot, T2W FSE frontal on a right-angle to the impar ligament, T2W FSE transverse on a right-angle to the flexor cortex of the navicular bone, T1W transverse parallel to the dorsal border of P3 and T1W frontal High Resolution or T1W 3D GRE frontal parallel to the flexor cortex of the navicular bone. In three of these five cases, additional sequences were conducted to investigate the articular indentation, T1W 3D sagittal and T1W 3D sagittal ISO.

Seven horses underwent prospective MRI using a specific designed study protocol that consisted of the following sequences: T2*W sagittal, T1W 3D sagittal, T1W 3D sagittal ISO, STIR sagittal, T2 FSE sagittal, T2 FSE HR sagittal, T1W 3D GRE frontal and T2 FSE frontal both parallel to the articular indentation. When possible, the frontal plane sequences were specifically aligned to be parallel to the defect to best assess the depth of the defect. In cases where the defect configuration was less distinct, a standard frontal plane orientation parallel to the axis of the foot was obtained.

Following MR scanning, the images were evaluated using a DICOM viewing software (RadiAnt DICOM Viewer). The size of the articular indentation was defined on the sagittal images of the T1W 3D ISO, which typically has a small slice thickness and separation (0.9 mm and 0.9 mm) combined with a high lesion contrast. In two retrospective cases, in a total of three feet the T1W 3D ISO was not performed, and the measurements were performed on the T2*W sagittal with a slice thickness of 0.77 mm and separation of 0.77 mm. The subchondral bone was subjectively evaluated for sclerosis and the presence of a concomitant cyst-like lesion with or without connection to the articular indentation.

Results

In total, 30 horses (**Table 1**) were included with a mean age of 8.5 years old (range: 1–21 years). Articular indentations were identified in only 2.9% (30/1041) of the investigated horses and in only 2.7% (45/1683) of all reviewed LM radiographs. The included study population consisted of 16 Warmbloods, 12 Friesians, 1 Haflinger horse and 1 Appaloosa horse. Friesians were clearly overrepresented as the standard hospital's population consists of only 13% Friesians. The remaining breeds, however, mimicked the hospital's population (59% Warmbloods, 2% Haflinger horses and 0.6% Appaloosas). There were 11 geldings, 7 stallions and 12 mares. In 50% of the horses (15/30), the articular indentation was identified in only one front limb. In the remaining 50% of the horses (15/30), the articular indentations were identified in both front (14/15) and hindlimbs (1/15). Based on the nature of this study, no reliable comparison between limbs could be made. Male horses were slightly overrepresented with 18/30 (60%). A total of 17/30 horses were presented with variable degrees of lameness. Following diagnostic anaesthesia, lameness was localised to the foot in 12 horses. Seven horses had significant pathology affecting the DIPJ which rendered additional intra-articular anaesthesia unnecessary, such as large extensor process fragmentation (3/7), standard extensor process fragmentation (1/7), Type III P3 fracture (1/7), Type VI P3 fracture (1/7) and severe osteoarthritis of the DIPJ (1/7). Other causes of foot lameness unrelated to the DIPJ were various and consisted of hoof canker, impar ligament desmitis, chronic laminitis, podotrochlear disease, keratoma and severe pododermatitis. Lameness unrelated to the foot were caused by osteoarthritis of the proximointerphalangeal joint (PIPJ), osteoarthritis of the radiocarpal joint (RCJ) and septic tenosynovitis of the carpal sheath. The cause of lameness remained undefined in two horses. The remaining 13 horses were presented for complete pre-purchase examination and were all sound during the clinical examination.

All 45 articular indentations, identified on the reviewed lateromedial radiographs, were subsequently categorised into four different indentation types (**Fig 2a-d**, **Table 1**). Thirty-six were classified as Type 1, 1 as Type 2, 6 as Type 3 and 2 as Type 4. A total of 12/15 cases that had bilateral indentations were diagnosed with a similar indentation type in the contralateral foot. Only 3/15 cases (Nr. 9, Nr. 21, Nr. 28) were diagnosed with different indentation types in the contralateral foot.

Distribution differed slightly between breeds (**Fig 4**). Type 1 articular indentations were more frequently identified in Friesian horses, while Types 2, 3 and 4 were only seen in Warmbloods. Interestingly, 6/7 horses with a Type 3 or Type 4 indentation were presented for general pre-purchase examination and were all sound. The Type 3 indentation in the remaining horse (Case Nr. 21, septic carpal tenosynovitis) was identified during standard clinical work-up. Furthermore, none of the corresponding radiographs (of the horses with a Type 3 or Type 4 indentation) showed any signs of degenerative joint disease. It is worthy to note, however, that all horses with a Type 3 and/or Type 4 were young horses (range 2–7 years), most of them at the beginning of their athletic career. In total, 36 corresponding dorsopalmar (DP) views were available for radiographic assessment. On only 23/36 DP views, a poorly defined and sagittal located lucency, potentially related to the articular indentation, was identified within the articular margin of the distal phalanx. All Type 3 and Type 4 indentations were consistently found on

TABLE 2: Categorisation of DIP joint osteoarthritis.

None	No osteo-arthritic signs
Mild	Minor osteophyte(s) at the distal articular margin of P2 and/or presence of minor osteophytes at the dorsoproximal margin of the navicular bone and/or presence of minor osteophytes at the extensor process
Moderate	Obvious osteophyte(s) at the distal articular margin of P2 and/or presence of obvious osteophytes at the dorsoproximal margin of the navicular bone and/or presence of obvious osteophytes at the extensor process
Severe	Marked osteophyte(s) at the distal articular margin of P2 and/or presence of marked osteophytes at the dorsoproximal margin of the navicular bone and/or presence of marked osteophytes at the extensor process

ReSolvin EQ™

Special Needs Nutrition for *Horses Prone to Gastric Ulcers*

Dietary supplementation of polyunsaturated fatty acids (PUFAs), particularly eicosapentaenoic acid (EPA), docosahexaenoic acid (DHA), and gamma-linolenic acid (GLA), has been a key focus of research efforts due to their positive effects in the body. Virtually every body cell features membranes composed of PUFAs, and these membranes are extremely responsive to dietary supplementation.

A study performed by Kentucky Equine Research assessed the relationship between red blood cell PUFAs and the incidence and severity of squamous gastric ulcers when horses were fed short-chain polyunsaturated fatty acids (SC-PUFAs) or long-chain polyunsaturated fatty acids (LC-PUFAs).*

Horses were evaluated by gastroscopy for squamous ulcer score, gastric pH, and blood fatty acid composition prior to supplementation and after three months of supplementation with a corn-flax oil blend, which included the SC-PUFAs alpha-linolenic acid (ALA) and linoleic acid (LA), or **ReSolvin EQ™**, a source of LC-PUFAs that contained GLA, EPA, and DHA.

Three months of supplementation with ReSolvin EQ increased red blood cell levels of GLA, EPA, DHA, DGLA (di-homo-gamma-linolenic acid), and AA (arachidonic acid) and reduced sever ulcer prevalence (38% in unsupplemented horses vs. 8% in horses supplemented with LC-PUFAs with a sever ulcer score, grade 3-4). SC-PUFA supplementation did not effectively elevate red blood cell GLA, EPA, DHA, DGLA, or AA, and severe ulcer incidence was not different (38% in unsupplemented horses vs. 23% in horses supplemented with SC-PUFAs with a sever ulcer score). Lower levels of RBC GLA, DGLA, AA, and EPA correlated with severe squamous cell gastric ulceration.

Targeted supplementation with ReSolvin EQ, a blend of GLA, EPA, and DHA, provides potent anti-inflammatory support for horses predisposed to gastric ulcers. *Learn more at ker.com/resolvin.*

KERx Special Needs Nutrition is a division of KER Targeted Nutrition that features products developed by Kentucky Equine Research and recommended by veterinarians to support specific nutrition-related challenges.

**Pagan, J.D., A.A. Hauss, E.C. Pagan, J.L. Simmons, and B.M. Waldridge. 2022. Long-chain fatty acid supplementation increases levels in red blood cells and reduces the prevalence and severity of squamous gastric ulcers in exercised Thoroughbreds. Journal of the American Veterinary Medical Association. doi: 10.2460/javma22.06.0275.*

Developed by:
Kentucky Equine Research®
info@ker.com ▪ +1.859.873.1988

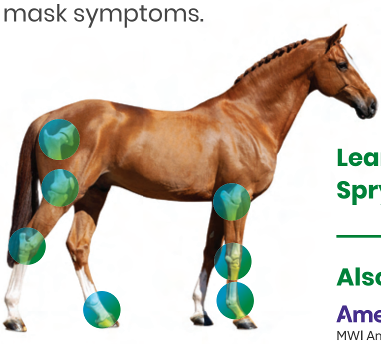
Manage lameness and joint issues with *confidence.*

With a single injection of Spryng™ with OsteoCushion™ Technology, you have the power to simply, effectively and economically manage lameness and joint issues.

Spryng™ with OsteoCushion™ Technology is an innovative veterinary medical device that takes the treatment of lameness issues into a new arena by addressing the root cause of the conditions — missing and damaged cartilage. Spryng™ aids in the management of joint pain from the loss of cartilage or tissue-bone mechanical malfunction caused by joint disfunction.

When injected into the joint, Spryng™ creates a sponge-like, shock-absorbing matrix — that works with synovial fluid to mimic the protective form and function of natural, healthy joint cartilage. When a horse jumps, runs or performs any movement with joint impact, Spryng™ absorbs and releases synovial fluid in response, with elastic stiffness that complements natural synovial fluid and cartilage dynamics.

Spryng™ also provides a natural scaffold, potentially protecting the joint from further injury, unlike other lameness management options that may only mask symptoms.



Learn more and order SpryngHealth.com

Also available at

AmerisourceBergen
MWI Animal Health®

VETCOVE

SIMPLE
Single injection with rapid results

LONG LASTING
Long duration of joint protection

INNOVATIVE
Address the affliction — helps to restore proper joint mechanics

A VETERINARY MEDICAL DEVICE

spryng™
with OsteoCushion™ Technology

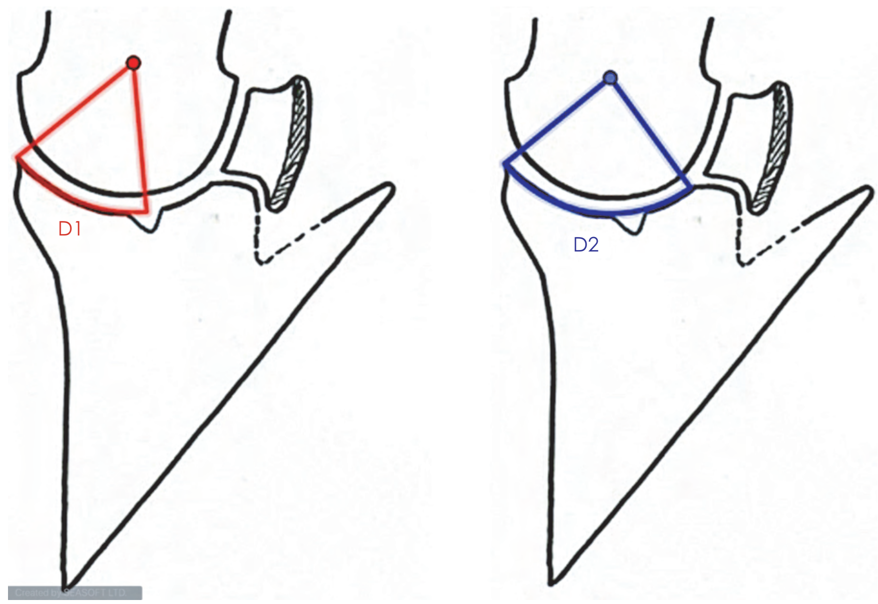


Fig 3: Schematic image showing the location of the articular indentation of the DIP joint and assessment of the D1 and D2 variables to calculate the D1 : D2 ratio. D1: Distance from the extensor process until the articular indentation, D2: The total length of the articular margin of P3.

both LM and DP views. The remaining types, however, were inconsistently identified on the DP view.

Osteoarthritic changes of the DIPJ were found in only 12/45 (26.7%) LM radiographs of the feet that were diagnosed with an articular indentation of the distal phalanx. Severity of changes varied between mild (7/12), moderate (3/12) and severe (2/12) (**Table 2**). The mean distance (D1:D2) from the extensor process until the articular indentation was 64.9% of the articular margin of P3 (range 54%–76%). Mean distance differed slightly between breeds, namely, 65.7% in the Friesian horse group, 64.2% in the Warmblood horse group, 73% in the Haflinger horse group and 57% in the Appaloosa horse group. Mean distance also differed slightly between indentation types, namely, 63.3% for Type 1 indentations, 62.0% for Type 2 indentations, 63.2% for Type 3 indentations and 68.5% for Type 4 indentations.

Following assessment of the prospective and retrospective retrieved MRI images, the articular indentation was found to be consistently located in the mid-sagittal (medial to lateral) plane and in the centre (from dorsal to palmar and medial to lateral) of the articular surface of P3 (**Fig 2a-d**). The articular indentations and its borders were best visible on the T1W sagittal ISO images, which typically has a small slice thickness. The indentations were also identified on T2*W and T2 FSE sagittal and frontal images, but with more difficulty. Small and shallow indentations were more

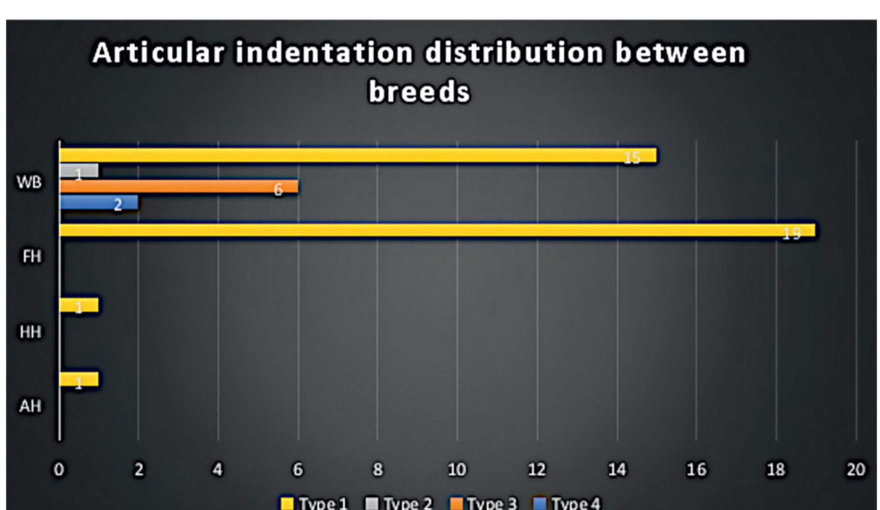


Fig 4: Distribution of the different articular indentation types within and between different horse breeds. WB, Warmblood horses; FH, Friesian horses; HH, Haflinger horses; AH, Appaloosa horses.

challenging to identify as the indentations did not much alter the normal variable shape of the third phalanx. The lateromedial size of the articular indentations ranged from ≤0.8 mm to ≤9.0 mm. Assessment of the surrounding sclerosis subjectively varied from mild to severe, with severe sclerosis only visible in combination with the larger articular indentations.

All radiographic types were evaluated by MRI scanning. Low-field MRI was able to identify several indentations related OCLLs that were not visible on the standard lateromedial radiographs of the foot. In total, six OCLLs were identified of which only three (Nr. 25, Nr. 27 and Nr. 28) were radiographically classified as a Type 3. The remaining three were radiographically scored as a Type 1 (Nr. 4, Nr. 16 and Nr. 18). Five were located in the middle of the articular surface on the sagittal image and had a clear communication with the radiographically visible articular indentation (Type 3). In one foot (Nr. 16), the OCLL was located dorsal to the indentation, but low-field MRI failed to identify a clear communication with the DIPJ. One horse (Nr. 4) had a rounded region in the sclerotic bone adjacent to the indentation in the subchondral bone. On T1 W, T2* W and T2 FSE, it consisted of a hypointense rim with a centre isointense to the medullary bone without an increased signal on STIR images. This was evaluated as an OCLL because of its shape and location, without a central fluid content. Moreover, none of the corresponding STIR images showed evidence of bone oedema surrounding the OCLL.

The cartilage layer overlying the indentation was mainly evaluated with the anatomical T1 GRE sagittal weighted sequence and was interpreted as abnormal in seven cases, i.e., having an irregular cartilage surface (Nr. 10, Nr. 14b and Nr. 16) or a decreased signal (Nr. 1, Nr. 25, Nr. 27 and Nr. 28) (**Table 3**). The small fragment overlying the articular indentation in Type 4 articular indentations was identified in one horse (Nr. 28) using the T1W 3D sagittal ISO sequence. In two horses (Nr. 4 and Nr. 18), however, no cartilage abnormalities were found despite the presence of an OCLL.

MRI evaluation generally indicated the presence of more severe signs of joint disease in most cases than what was identified radiographically (**Table 3**). However, in three cases (Nr. 1, Nr. 14 and Nr. 15), the degree of joint disease was found to be similar to the radiographic OA grade. Additional joint pathologies identified were an extensor process fracture, Type III P3 fracture, an OCLL in the opposing subchondral bone of the second phalanx.

Discussion

This article describes the exact location of a relatively rare indentation of the articular margin of P3 seen on plain LM radiographs of the equine foot. Articular indentations were typically identified in the third quarter (from dorsal to palmar/plantar, range 54%–76%) of the articular margin of P3. Radiographically, only eight articular indentations (Types 3 and 4) had concurrent mild-to-moderate subchondral lucencies, i.e., subchondral cystic lesions (OCLLs). One Type 3 (Nr. 25) and two Type 4 (Nr. 27 and Nr. 28) radiographic identified indentations underwent complementary MRI examination. MRI confirmed the presence of the three radiographically diagnosed OCLLs and identified the presence of three additional OCLLs in cases where the articular indentation was radiographically categorised as a Type 1. Five OCLLs communicated with the radiographically visible articular indentation.

The main purpose of this study was to give a detailed morphological description of the articular indentation of the articular margin of the distal phalanx. Therefore, the exact aetiopathogenesis of this specific radiographic identifiable articular indentation remains unclear. Based on its consistent intra-articular localisation and potential communication with underlying OCLLs (Type 3 and Type 4), a similar etiopathogenesis as opted for true OCLLs seems likely. Common reported hypotheses for OCLLs are developmental diseases (such as osteochondrosis), local trauma and focal osteolysis as a result of sepsis (Sherlock & Mair, 2011; Von Rechenberg et al., 1998). In this study, however, by using case's history, local trauma and sepsis was excluded as possible inciting causes for the development of articular damage. Therefore, the authors believe that developmental diseases, such as osteochondrosis, could form a possible explanation for the development of the indentation. However, as the number of horses and breeds included in this study were small and no histopathology was performed in any of these cases, this merely remains a hypothesis that still needs to be proven. Histopathology is necessary to differentiate between the different inciting causes.

The articular indentations investigated in this study were encountered equally in Warmbloods and Friesian horses. In the Netherlands, around 7% of the horse population are Friesians (Van Vliet & Back, 2006), and even though our hospital's caseload comprises a higher percentage of Friesian horses (13%), the Friesian breed seemed clearly overrepresented in this study (40%). Furthermore, it is noteworthy to mention that all Type 3 and Type 4 articular indentations were identified in Warmblood horses only. In Literature, Thoroughbreds and Warmblood horses have frequently been reported to be overrepresented for the development of phalangeal cysts (Haack et al., 1983; Story & Bramlage, 2004; Rechenberg et al., 1998).

The vast majority (43/45) of articular indentations were identified in the front-feet. This unequal distribution could be partially explained by the inclusion of multiple pre-purchase examinations, as radiographic screening of the hind feet was not standard in our clinic. Additionally, 17 of the 30 horses were referred for lameness work-up of which 16 were diagnosed having a front limb lameness.

To date, the exact clinical significance of the different articular indentation types remains unclear. True OCLLs of P3, on the other hand, are frequently associated with variable lameness degrees (Butler et al., 2008; McIlwraith, 1990; Trotter & Dyson, 2003). Lameness has been attributed to persistent synovitis and degenerative joint disease (Butler et al., 2008), an increased pressure in the subchondral bone or cyst, or a combination of one of these (Kold & Hickman, 1986). Furthermore, subsequent cavitation of the surrounding bone could potentially lead to a pathological fracture (Scott et al., 1991). Recently, Peter and colleagues (2018) reported on DIPJ lameness in Thoroughbred racehorses caused by an OCLL of P3. In eight cases, an associated indentation in the articular surface of P3 could be identified on the lateromedial or oblique projections. In contrast to Peter et al. (2018), no clear relationship between the indentation and lameness was found in this study, as 43% (13/30) of the horses were admitted for standard prepurchase examinations and were sound at presentation. Interestingly, all horses with a

TABLE 3: MRI findings.

Case No.	Limb	Prospective/ retrospective	Minimal size (mm) sagittal	Minimal size (mm) frontal	Subchondral bone sclerosis	Arthrosis Classification	Cartilage overlying the indentation	Cyst present
1	LF	P	4.5	0.4	Mild	None	Decreased signal	No
4	LF	P	5.4	0.8	Moderate	Moderate	Normal	Yes
5	LF	R	0.8	0.8	Moderate	Mild	Normal	No
5b	RF	R	0.4	X	Moderate	Moderate	Normal	No
10	RF	R	6.3	0.8	Mild	Moderate	Normal	No
10b	LF	R	6.3	3.1	Moderate	Moderate–Severe	Irregular	No
14	LF	P	5.4	0.4	Mild	Mild	Normal	No
14b	RF	P	3.6	3.9	Mild	Mild	Irregular	No
15	LF	R	0.8	X	Mild	Mild	Normal	No
15b	RF	R	0.8	X	Mild	Mild	Normal	No
16	LF	P	5.4	3.1	Severe	Moderate	Irregular	Yes
18	LF	R	3.6	0.8	Moderate	Mild	Normal	Yes
25	LF	P	4.5	0.8	Severe	Moderate	Decreased signal	Yes
26	RF	R	9.0	X	Severe	Mild	Normal	No
27	LF	P	7.2	4.6	Severe	Moderate	Decreased signal	Yes
28	LF	P	2.7	1,5	Moderate	Moderate	Decreased signal	No
28b	RF	P	3.6	3.9	Moderate	Mild–Moderate	Normal	Yes

Abbreviations: LF, left front limb; RF, right front limb; X, not visible.

radiographic identified articular indentation and concomitant OCLL (Type 3 and Type 4) were sound (6/7 horses) or had pathology unrelated to the foot (1/7 horses). Lameness in the remaining 17 horses was reported to be caused by a variety of pathologic conditions other than the articular indentation. However, as no intra-articular anaesthesia was performed in any of these cases, no definitive conclusions regarding the clinical relevance could be made.

Multiple studies have reported on the use of MRI and CT for assessment of OCLLs of P3 (Mair & Sherlock, 2008; Schön et al., 2017; Sherlock & Mair, 2011). To the author's knowledge, however, none have specifically focused on the articular indentation which is described in this paper. Despite the superior image resolution of high-field MR scanners, low-field MR imaging has been used for the detection of full thickness and severe cartilage alterations in the DIPJ (Olive, 2010). Subtle and partial thickness defects, on the other hand, are difficult or even impossible to detect with low-field MR systems (Van Zadelhoff et al., 2019). By using a low-field MR scanner, cartilage abnormalities were found in only 41% of the cases scanned in this study. Besides the detection of cartilage abnormalities, low-field MR was capable to identify subchondral bone sclerosis surrounding the articular indentation in all cases. In this study, cartilage abnormalities were most frequently identified on T1W 3D ISO and T1 GRE sagittal weighted sequences.

This study provides a detailed radiographic description with correlating MRI findings of a rare indentation of the articular surface of P3. Four different indentation types were identified radiographically. Concomitant MRI findings were varied and ranged from slight subchondral contour deviations to clear articular indentations with related OCLLs. Low-field MRI has, despite its limitations, proven to be a useful and excellent imaging modality for evaluation of this rare articular indentation and its surrounding subchondral and trabecular bone. Although none of the lamenesses seemed directly related with the articular indentation, the true clinical relevance remains unclear at this time as no intra-articular anaesthesia or long-term follow-up was performed. Nevertheless, intra-articular fragmentation and OCLLs, whether or not communicating with the synovial cavity, are known to potentially initiate synovitis, osteoarthritis and future lameness. Therefore, it seems rational, however, to assume that horses with a radiological visible OCLLs (Type 3 and Type 4) or an indentation in combination with a fragment (Type 2) are at an increased risk for future unsoundness. The authors of this study, therefore, do recommend careful assessment of the LM and upright pedal view when articular indentations are encountered. Since OCLLs are easily missed with radiography alone, additional MRI is advised in horses with a radiographic visible articular indentation and proven DIPJ lameness. Additional studies are necessary to investigate the exact aetiology of the articular indentation, the risk for progression of one type into another and its potential for initiating osteoarthritis and subsequent lameness.

Authors' declarations of interest

No conflicts of interest have been declared.

Ethical animal research

Not applicable to this retrospective study.

Source of funding

This research was realised in collaboration with Hallmarq Veterinary Imaging Ltd. Hallmarq Veterinary Imaging Ltd. funded multiple (i.e. nine) magnetic resonance examinations.

Authorship

S. Frietman and N. De Heer contributed to study design, study execution, data analysis and interpretation and preparation of the manuscript. C. Van Aert contributed to data analysis and interpretation and preparation of the manuscript. All authors gave their final approval of the manuscript.

References

Baxter, G.M. (1996) Subchondral cystic lesions in horses. In: *Joint Disease in the Horse*. Eds: McIlwraith, C.W. & Trotter, G.W., W.B. Saunders, Philadelphia. pp. 384-397.

Butler, J., Colles, C., Dyson, S., Kold, S. & Poulos, P. (2008) Foot pastern and fetlock. *Clinical Radiology of the Horse*, 3rd edition. West Sussex: John Wiley and Son, pp. 16–187.

Dyson, S.J., Murray, R., Schramme, M.C. & Branch, M. (2003) Magnetic resonance imaging of the equine foot: 15 horses. *Equine Veterinary Journal*, **35**, 18–26.

Dyson, S.J., Murray, R. & Schramme, M.C. (2005) Lameness associated with foot pain: results of magnetic resonance imaging in 199 horses (January 2001-December 2003) and response to treatment. *Equine Veterinary Journal*, **37**, 113–121.

Fürst, A., Kaegi, B., von Rechenberg, B. & Auer, J.A. (1997) Die Behandlung von 5 Pferden mit subchondralen zystoiden Defekten im Fesselbein. *Pferderheilkunde*, **13**, 147–161.

Garcia-Lopez, J.M. & Kirker-Head, C.A. (2004) Occult subchondral osseous cyst-like lesions of the equine tarsocrural joint. *Veterinary Surgery*, **33**, 557–564.

Haack, D., Hertsch, V. & Baez, C. (1983) Zystoide Defekte im Hufbein des Pferdes. *Pferdeheilkunde*, **4**, 143–153.

Kold, S. & Hickman, J. (1986) An experimental study of the healing process of equine chondral and osteochondral defects. *Equine Veterinary Journal*, **18**, 18–24.

Konde, L.J. (1998) Aggressive versus nonaggressive bone lesions. In: *Textbook of Veterinary Diagnostic Radiology*. Ed: Thrall, D.E., W.B. Saunders, Philadelphia. pp. 37-43.

Mair, T.S. & Sherlock, C.E. (2008) Osseous cyst-like lesions in the feet of lame horses: Diagnosis by standing low-field magnetic resonance imaging. *Equine Veterinary Education*, **20**, 47–56.

McIlwraith, C.W. (1990) Subchondral cystic lesions in the horse – the indications, methods and results of surgery. *Equine Veterinary Education*, **2**, 75–80.

Olive, J. (2010) Distal interphalangeal articular cartilage assessment using low-field magnetic resonance imaging. *Veterinary Radiology & Ultrasound*, **51**, 259–266.

Peter, V.G., O'Keeffe, T.A., Smith, L.C.R. & Schweizer-Gorgas, D. (2018) Radiographic identification of Osseous cyst-like lesions in the distal phalanx in 22 lame thoroughbred horses managed conservatively and their racing performance. *Frontiers in Veterinary Science*, **5**, 1–7.

Schön, S., Fürst, A.E., Ohlerth, S., Kircher, P.R., Roos, M. & Jackson, M.A. (2017) Computed tomographic versus radiographic assessment of the visibility and features of subchondral cystic lesions in equine limbs. *Pferdeheilkunde*, **33**, 256–262.

Scott, E.A., Snyder, S.P., Schmotzer, W.B. & Pool, R. (1991) Subchondral bone cysts with fractures of the extensor processes in a horse. *Journal of the American Veterinary Medical Association*, **199**, 595–597.

Sherlock, C. & Mair, T. (2011) Osseous cyst-like lesions/subchondral bone cysts of the phalanges. *Equine Veterinary Education*, **23**, 191–204.

Story, M.R. & Bramlage, L.R. (2004) Arthroscopic debridement of subchondral bone cysts in the distal phalanx of 11 horses (1994–2000). *Equine Veterinary Journal*, **36**, 356–360.

Trotter, G. & Dyson, S. (2003) Osseous cyst like lesions in the distal phalanx. In: *Diagnosis and Management of Lameness*. Eds: Ross, M. & Dyson, S., W.B. Saunders, St. Louis. p. 317.

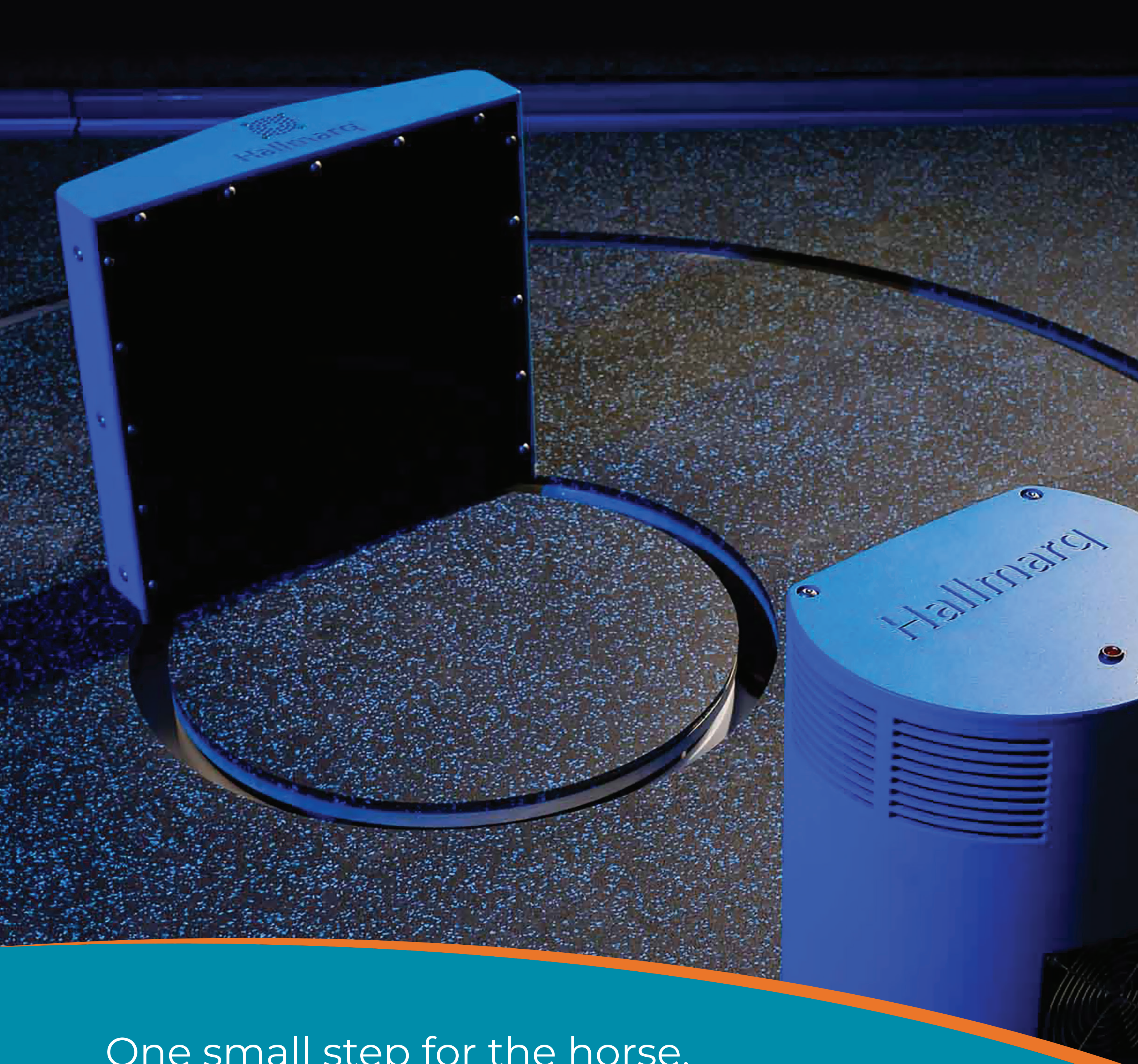
Van Suntum, M. & Hartung, K. (1989) Zur Erkennbarkeit subchondraler zytoider Defekte an den distalen Extremitätengelenken des Pferdes. *Tierärztl Prax*, **17**, 79–83.

Van Vliet, L.M.W. & Back, W. (2006) Quantitative analysis of genetic traits related to Friesian horses admitted to a veterinary teaching hospital (1995-2003). In: Proceedings of European Veterinary Conference Voorjaarsdagen, Amsterdam. p. 68

Van Zadelhoff, C., Schwarz, T., Smith, S., Engerand, A. & Taylor, S. (2019) Identification of naturally occurring cartilage damage in the equine distal interphalangeal joint using low-field magnetic resonance imaging and magnetic resonance arthrography. *Frontiers in Veterinary Science*, **6**, 508.

Von Rechenberg, B., McIlwraith, C.W. & Auer, J.A. (1998) Cystic bone lesions in horses and humans: a comparative review. *Veterinary and Comparative Orthopaedics and Traumatology*, **11**, 8–18.

Young, A.C., Dimock, A.N., Puchalski, S.M., Murphy, B. & Spriet, M. (2012) Magnetic resonance and radiographic diagnosis of osseous resorption of the flexor surface of the distal phalanx in the horse. *Equine Veterinary Journal*, **44**, 3–7.


Hallmarq
Hallmarq


ALL OTHERS
FALL SHORT.
ANTACID
GLUTAMINE SUPPLEMENT
PSYLLIUM
PREBIOTIC SUPPLEMENT
ABC SUPPLEMENT
OMEPRAZOLE
PROBIOTIC SUPPLEMENT
FOR ANIMAL USE ONLY – FOR HORSES
AssureGuard Gold
The Ultimate Digestive Aid
Pelleted Equine Performance Digestive Aid with Antacid
Proprietary GST® Technology
ARENUS ANIMAL HEALTH
Net Weight: 25 lb (11.3 kg) - 85 Servings
Assure® Guard Gold
The Ultimate Digestive Aid®
The Trusted Solution of Equine Veterinary Professionals.
Researched and Patented for the treatment of Recurrent Colic, Chronic Diarrhea, Dysmotility and Ulcers.
ARENUS® ANIMAL HEALTH
Arenus Animal Health | 866-791-3344 | www.arenus.com
Ask one of our Veterinary Solutions Specialists how Assure Guard Gold and the new Assure Advisor Mobile App can help you guide your patients to improve digestive health.

Equine vet. Educ. (2022) **34** (12) 635
doi: 10.1111/eve.13557_1

Original Article

Comparison of the diagnostic predictability of serum amyloid A, white blood cell count and immunoglobulin G tests as indicators of early-onset, acute-phase morbidities in newborn foals

N. M. Nieman[†]* and D. S. Chan[‡]

[†]WinStar Farm, Versailles, Kentucky, USA; and [‡]Epona Biotech Institute of Technology Campus, Sligo, Ireland
*Corresponding author email: nniemandvm@winstarfarm.com

N. M. Nieman Present address: WinStar Farm, Versailles, Kentucky, USA
D. S. Chan Present address: Epona Biotech, Institute of Technology Campus, Sligo, Ireland

Keywords: horse; serum amyloid A; foal; diagnostic blood test; white blood cell count; immunoglobulin G

Summary

Background
Acute-phase proteins (APPs) have diagnostic value as nonspecific, early indicators of inflammation and infectious disease.

Objectives
To assess the ability of serum amyloid A (SAA) testing to distinguish between healthy and nonhealthy newborn foals, and to compare the diagnostic predictability of SAA with white blood cell (WBC) counts and serum immunoglobulin G (IgG) concentration.

Study design
Three-year prospective clinical evaluation and diagnostic sample collection from newborn foals.

Methods
Following an examination, a blood sample was obtained from each foal and tested for SAA and IgG concentrations, complete blood count (CBC) and standard biochemistry values. Foals were categorised as healthy or nonhealthy based on the clinical examination. The presence of clinical signs of infectious origin or certain noninfectious morbidities with a pro-inflammatory component was sufficient for a nonhealthy designation. Serum amyloid A, IgG and WBC test results were determined and compared for healthy and nonhealthy foals.

Results
A total of 24 (13.7%) foals were diagnosed as clinically sick and 151 (86.3%) as normal based on physical examinations performed within 24 h after parturition. Mean SAA values were 27.7 $\pm$ 129.0 mg/L and 247.2 $\pm$ 454.8 mg/L for healthy and nonhealthy foals, respectively, a significant ($p < 0.05$) difference indicating that elevated SAA values are associated with a nonhealthy diagnosis. Using a positive threshold of 100 mg/L, the SAA test had a positive predictive value (PPV) of 55.6% and IgG had the lowest PPV (16.7%) followed by WBC count (23.3%).

Main limitations
A larger number of clinically nonhealthy foals with SAA levels >100 would have given the study greater statistical power.

Conclusions
Equine practitioners can consider SAA testing to be a reliable newborn examination diagnostic tool for detecting early-onset, acute-phase infection or noninfectious morbidities with an inflammatory component.

Clinical relevance

- Serum amyloid A screening functioned as a sensitive interpretive marker of infectious and other inflammatory morbidities in neonatal foals, a high-risk equine population that potentially benefits from early therapeutic intervention.
- A novel SAA testing device validated for use in horses provided rapid and convenient point-of-care screening for SAA in an equine neonatal examination setting.

EQUINE VETERINARY EDUCATION
Equine vet. Educ. (2022) **34** (12) 636
doi: 10.1111/eve.13592_1

Original Article

Evaluation of fingertip pulse oximeters for monitoring haemoglobin oxygen saturation in arterial blood and pulse rate in isoflurane-anaesthetised horses breathing greater than 90 percent oxygen

A. M. Sage, T. D. Ambrisko* , F. D. C. Martins, S. C. Dantino, S. C. J. Keating, D. E. Strahl-Heldreth and P. A. Wilkins

Department of Veterinary Clinical Medicine, College of Veterinary Medicine, University of Illinois at Urbana-Champaign, Urbana, Illinois, USA
**Corresponding author email: tambrisko@hotmail.com*

Dr. A. M. Sage's present address: Department of Surgical Science, University of Wisconsin-Madison School of Veterinary Medicine, Madison, Wisconsin, USA
Dr. F. D. C. Martins's present address: Department of Veterinary Medicine and Surgery, University of Missouri College of Veterinary Medicine, Columbia, Missouri, USA
Dr. S. C. Dantino's present address: Department of Large Animal Clinical Sciences, University of Tennessee College of Veterinary Medicine, Knoxville, Tennessee, USA

Keywords: horse; anaesthesia; pulse oximetry; oxygen saturation; accuracy

Summary

Background
Pulse oximetry is a noninvasive method for continuous monitoring of oxygen saturation (SpO_2) and pulse rate (PR) used in equine anaesthesia. Despite species differences in the oxyhaemoglobin dissociation curve, pulse oximeters validated for humans are commonly used in veterinary medicine. These devices are expensive and at an increased risk for damage when used for equine anaesthesia. Human fingertip pulse oximeters (FPO) may be useful as an inexpensive alternative to standard devices.

Objectives
Evaluate accuracy and repeatability of FPOs applied to tongues of anaesthetised horses breathing >90% oxygen.

Study design
Prospective clinical study.

Methods
Duplicate SpO_2 and PR measurements from eight pulse oximeters (PO; seven FPOs and reference PO) placed in random order on tongues of horses under inhalational anaesthesia were recorded. A standard portable PO (RPO) was used as reference SpO_2 and invasive blood pressure trace or manual pulse palpation as reference PR. Non-parametric Bland-Altman analysis was performed. Acceptable coefficient of repeatability value was $\leq$6% SpO_2. Agreements were accepted if limits of agreement were $\leq \pm$3% difference in SpO_2 and $\leq \pm$10% relative difference in PR. Only PR values between 25 and 50 beats per minute and their corresponding SpO_2 measurements were used for agreement analysis.

Results
SpO_2 repeatability and agreement were unacceptable for all devices. The agreement of PR measurements was acceptable for one FPO and the RPO.

Main limitations
Utilisation of devices designed for the human oxyhaemoglobin dissociation curve, high number of absent or erroneous readings, use of healthy horses, small sample size, unavailability of co-oximetry, lack of a desaturation protocol and difficulty with proper placement of FPOs on horse tongues are all considered limitations in this study.

Conclusions
Accuracy of FPOs used in anaesthetised horses was poor. Their use in equine anaesthesia for SpO_2 monitoring is not recommended, but some models may be considered for continuous PR monitoring in conjunction with intermittent manual confirmation.

Clinical relevance

- SpO_2 and pulse rate should be monitored in horses during general anaesthesia and the recovery period, especially in field settings when oxygen supplementation is not typically provided.
- Pulse oximeters are expensive, and a clinician may not choose to use one due to risk of damage of equipment. A lower cost option may reduce the concern for damage.
- This study demonstrates that human FPOs placed on horse tongues do not accurately measure SpO_2 but certain models may be suitable to monitor pulse rate. Based on findings in this study, their use as a monitor in horses under inhalant anaesthesia is limited.

Equine vet. Educ. (2022) **34** (12) 637
doi: 10.1111/eve.13590_1

Original Article

In vitro flow rates through five different catheters intended for intravenous use in horses at two different heights

***S. Lord*[†,*]*, J. Duncan*[†]*, M. Gozalo-Marcilla*[†] *and K. Woodhouse*[‡]**

[†]*Veterinary Clinical Sciences, The Royal (Dick) School of Veterinary Studies and The Roslin Institute, The University of Edinburgh, Midlothian; and* [‡]*School of Medicine, Veterinary Medicine and Life Sciences, University of Glasgow, Glasgow, UK*
**Corresponding author email: slord@ed.ac.uk*

Keywords: horse; fluid therapy; colic; anaesthesia

Summary

Background
Fluid therapy is an important component of equine practice. The choice of intravenous catheter is likely to impact fluid flow rates which is of relevance in clinical cases.

Objectives
(i) To assess fluid flow rates through five different equine catheters; (ii) to evaluate the impact of height on fluid flow rates and (iii) to compare agreement of flow rates achieved through identical catheters.

Study design
In vitro experimental study.

Methods
Flow rates were measured through five different equine catheters (2 × 14, 13, 12 and 10-gauge) at 150 and 200 cm from ground level. Each catheter was attached to a standardised fluid administration system, and time taken to reach 1000 g of fluids was measured. Three of each catheter were used to assess the agreement between identical catheters. Statistical analysis: (i) one-way ANOVA assessed whether catheter type influenced flow rate and a post hoc Tukey's test compared mean flow rates to all other flow rates; (ii) two-way ANOVA assessed whether height and catheter type influenced the flow rate. Finally, (iii) an intraclass correlation assessed how closely flow rates from identical catheters resembled each other.

Results
(i) The fastest mean flow rates were achieved through the 10-gauge catheter at 150 (14.1 L/h) and 200 cm (17.8 L/h). (ii) Mean flow rates through all five catheters increased by a range of 25.4–28.6% at 200 vs. 150 cm. (iii) There was excellent agreement between mean fluid rates through identical catheters (intraclass correlation 0.994–0.998).

Main limitations
Flow rates achievable in vivo are likely to be lower. We used water which may have a different viscosity compared with fluids used commonly in equine practice.

Conclusions
Fluid flow rates can be increased using wider bore catheters and increasing the height of the fluid bag. There is an excellent agreement between fluid flow rates through identical catheters.

Clinical relevance

- This article may assist the equine practitioner to choose an appropriate catheter when rapid fluid administration is required.
- This in vitro study will provide information on other ways to increase fluid flow rates, for example by elevating the height of the fluid bag.
- The results presented here will reassure equine veterinary practitioners that flow rates between identical catheters intended for use in horses are very closely correlated.

EQUINE VETERINARY EDUCATION
Equine vet. Educ. (2022) **34** (12) 638
doi: 10.1111/eve.13573_1

Original Article

Prevalence of salmonella faecal shedding in at-risk hospitalised cases in an equine hospital in New Zealand: A pilot study

H. Lambe and B. W. Sykes*

School of Veterinary Science, Massey University, Palmerston North, New Zealand
**Corresponding author email: b.sykes@massey.ac.nz*

Keywords: horse; biosecurity; diarrhoea; PCR; culture

Summary

Background
Salmonella is an important veterinary pathogen contributing to gastrointestinal disease in horses and foals. Hospital biosecurity is an important consideration in preventing transmission between patients, and zoonotic transmission. The prevalence of salmonella in horses in equine hospitals has previously been reported in the USA and Australia. However, to date, it has not been reported in New Zealand.

Objective
The aim of this study was to identify the prevalence of salmonella faecal shedding in at-risk patients undergoing testing by repeated faecal culture or faecal PCR in an equine hospital in New Zealand.

Study design
Retrospective cohort study.

Methods
Medical records from a 2-year period (July 2018–June 2020) were reviewed. Patients identified by the treating clinician as at-risk of salmonella, and subsequently tested with repeated faecal culture (at least three samples) or faecal PCR were included for analysis. Descriptive analysis was used, and prevalence data reported with 95% confidence intervals.

Results
Twenty-eight horses were included in the final analysis. The overall prevalence of salmonella in the study population was 10.7% (n = 3/28, 95% CI 3.1–25.9%).

Main limitations
Small sample size (n = 28) and retrospective study design provide support for further investigation.

Conclusions
The prevalence of salmonella in the study population is comparable to previous reports from the USA. Further research into the prevalence and risk factors associated with faecal shedding of salmonella in hospitalised horses in New Zealand is warranted.

Clinical relevance

- Salmonella represents a significant veterinary pathogen due to its contribution to potential severe gastrointestinal disease in equine patients, human health and safety concerns through zoonotic transmission, and resulting impacts to patient care and business finances.
- Prevalence of salmonella faecal shedding in hospitalisation is important in guiding biosecurity practices and standard operating procedures within equine hospitals.
- Regular audits are an essential tool to ensure compliance with hospital biosecurity policies.


The Future of Arthritis
Treatment is Now
ARTHRAMID® VET
A new class of injectable joint therapy to treat equine osteoarthritis.


When it comes to equine nutrition, vets come to us.
As a veterinarian, you know there's a lot that rides on a horse's nutrition.
Did you also know there's one trusted resource for developing effective feeding solutions—and it's free? We have a create-your-own nutritional toolkit designed for vets. Backed by our equine research and innovation team, these tools help your staff diagnose and prescribe treatments.
We'll ship you the free toolkit that includes:
• Clinical disorders booklet
• Weight tapes
• Body condition scoring and topline evaluation handouts
• Vet solution cards for the most common conditions
• Guide to rehabilitating the neglected horse
Keeping horses healthy, and owners happy, makes us all feel good.
REQUEST YOUR FREE NUTRITION TOOLKIT:
VetNutritionInfo.com
Cargill®
Educational Partner of the American Association of Equine Practitioners
Visit us at this year's AAEP Conference:
Booth 11071
© 2022 Cargill, Incorporated. All rights reserved.

EQUINE VETERINARY EDUCATION
Equine vet. Educ. (2022) **34** (12) 639
doi: 10.1111/eve.13588_1

Original Article

Oral prednisolone achieves measurable concentrations in equine synovial fluid within 3 hours of administration: Preliminary observations

***D. W. Ramey*[†,*] *and H. K. Knych*[‡]**

[†]Ramey Equine, Chatsworth, California; and [‡]K.L. Maddy Equine Analytical Chemistry Laboratory, Davis, California, USA
**Corresponding author email: rameyequine@gmail.com*

Keywords: horse; arthritis; corticosteroid; joint; prednisolone

Summary

Background
Clinical and anecdotal evidence exists for the use of orally administered prednisolone in the treatment of osteoarthritis in humans; however, prednisolone is not commonly prescribed by this route of administration in horses for the treatment of osteoarthritis.

Objectives
This preliminary study tested the hypothesis that orally administered prednisolone could be detected in equine synovial fluid 3 h after administration.

Study design
Pre/post study.

Methods
Six horses were used in this study. Blood was drawn pre-prednisolone administration to assure that all horses were prednisolone free. Three hours after being given 400 mg prednisolone per os, an additional blood sample was taken, as well as samples from the radiocarpal (RC) and tibiotarsal (TT) joints. Samples were frozen and sent to the laboratory for determination of the presence of prednisolone using liquid chromatography-tandem mass spectrometry.

Results
Prednisolone appeared in measurable concentrations in the blood (Mean = 92.655 ng/ml; SD = 54.95 ng/ml) and synovial fluid (RC Mean = 28.44 ng/ml; SD = 20.58 ng/ml and TT Mean = 20.33; SD = 15.67 ng/ml) of all horses when tested 3 h after administration.

Main limitations
This study did not test for any possible therapeutic effects of oral prednisolone in osteoarthritis. It did not attempt to establish a therapeutic dosage for the medication, nor did it attempt to establish the pharmacokinetics of the medication.

Conclusions
Orally administered prednisolone appears in equine blood and synovial fluid at 3 h post-administration. Since it appears in joint fluid at concentrations that have been shown to be therapeutic for other corticosteroids, orally administered prednisolone could possibly have potential value as a therapeutic agent in the treatment of equine osteoarthritis, however further studies are required to investigate this.

Clinical relevance

- Orally administered prednisolone can be detected in equine synovial fluid 3 h after administration.
- Orally administered prednisolone has been shown to be an effective treatment in human osteoarthritis.
- Orally administered prednisolone deserves further investigation as a therapeutic option for equine osteoarthritis.

EQUINE VETERINARY EDUCATION
Equine vet. Educ. (2022) **34** (12) 640
doi: 10.1111/eve.13604_1

Original Article

Small intestinal intussusception in horses: Multicentre retrospective report on 26 cases (2009-2020)

R. Haddad[†], G. Corraretti[‡], O. Simon[‡], T. Mair[§], A. G. Sutton[†] and G. Kelmer[†,*]

[†]Department of Large Animal Medicine and Surgery, Koret School of Veterinary Medicine - Veterinary Teaching Hospital, The Hebrew University of Jerusalem, Rehovot, Israel; [‡]Equine Clinic De Morette, Asse, Belgium; and [§]Bell Equine Veterinary Clinic, Maidstone, Kent, UK
**Corresponding author email: gal.kelmer@mail.huji.ac.il*

O. Simon's present address: School of Animal and Veterinary Sciences Equine Health and Performance Centre, University of Adelaide, Adelaide, Australia

Keywords: horse; intussusception; outcome; retrospective; small intestine

Summary

Background
Intussusception is an infrequent cause of equine colic, most commonly encountered in young horses. This condition occurs due to abnormalities of motility and frequently includes the caecum.

Objectives
The purpose of this study was to review cases of equine small intestinal (SI) intussusception excluding those with caecal involvement.

Study design
Case series analytical retrospective study.

Methods
Medical records of all horses that had SI intussusception, not involving the caecum, from three equine clinics between 2009 and 2020 were reviewed. Information obtained included the following: clinical parameters, surgical or necropsy findings, complications and outcome. The Mann–Whitney *U*-test was used to compare outcome and complications with various parameters. Fisher's exact test was used to compare short-term survival with categorical variables. Significance was set at $p \leq 0.05$.

Results
Twenty-six horses met the inclusion criteria. The median age of horses was 9 months (interquartile range 2.8 months-6.5 years). Relevant history included diarrhoea and general anaesthesia. Twenty-two out of 26 horses were diagnosed during surgery, and 4 at necropsy. During surgery, 5 horses were subjected to euthanasia, 9 underwent manual reduction, and 8 underwent resection and anastomosis. The post-operative complication rate was high at 47% and included ileus, diarrhoea and colic. The prognosis decreased when the involved segment was longer ($p = 0.032$), lactate levels were higher ($p = 0.024$), and reflux was present before admission ($p = 0.024$). Of all horses, 53% survived to discharge; 92% of these survived for >1 year post-operatively (one case was lost to follow-up).

Main limitation
The retrospective nature of the study and the low number of cases included.

Conclusions
Small intestinal intussusception was diagnosed in horses of a variety of breeds and ages. Alterations in motility can predispose to intussusception, not only due to hypermotility (diarrhoea) but also due to hypomotility (anaesthesia). The prognosis for hospital discharge was fair; however, following hospital discharge, the long-term survival rate is high, and complications are rare.

Clinical relevance

- This study describes the clinical presentation, signalment and aetiology of horses suffering from a rare pathology, which could aid clinicians in diagnosing small intestinal intussusceptions more rapidly.
- High complication rates after surgical correction of small intestinal intussusceptions should be expected, and those horses should be treated accordingly.
- Long-term prognosis found in this study is good, and long-term complications are rare. This fact may help clinicians and owners in decision-making.

The study was accepted for presentation in part at the ECVS Annual Scientific Meeting 2020.


THE PERFECT PAIR
Give your patients the vaccine protection they deserve
Core EQ Innovator
5
Fluvac Innovator®
Visit ZoetisEquine.com for more information.
All trademarks are the property of Zoetis Services LLC or a related company or a licensor unless otherwise noted.
© 2021 Zoetis Services LLC. All rights reserved. COR-00177
zoetis

EVERY DAY LOW PRICE

Vetivex® Fluid Therapy

- **1000 mL bags are PVC FREE, DEHP FREE and LATEX FREE**
- **3000 mL and 5000 mL bags are LATEX FREE**
- **All bags have color coded ports**
- **24/7 technical support at 866-933-2472**
  support@dechra.com, www.dechra-us.com

To order, please contact your Dechra or distributor representative or call (866) 683-0660.

Dechra
Veterinary Products

08AD-VEQ21001-0521

Equine vet. Educ. (2022) **34** (12) 641
doi: 10.1111/eve.13615_1

Original Article

Complications, outcome and owner satisfaction after Callicrate Bander phallectomy and perineal urethrostomy in 14 equids

***T. Maurer*[†,*], *H. P. Brünisholz*[†], *T. O'Brien*[‡], *M. Coleridge*[‡], *M. D. Klopfenstein-Bregger*[†] and *C. Koch*[†]**

[†]*Department of Clinical Veterinary Science, Vetsuisse Faculty, Swiss Institute of Equine Medicine, University of Bern, Bern, Switzerland; and* [‡]*Fethard Equine Hospital, Fethard, Tipperary, Ireland*
**Corresponding author email: thimo.maurer@vetsuisse.unibe.ch*

M. Coleridge's present address: Rossdales Equine Hospital, Cotton End Road, Exning, Newmarket, Suffolk, CB8 7NN, UK

Keywords: horse; callicrate; penile squamous cell carcinoma; phallectomy; urethrostomy

Summary

Background
The use of a bander castration device (Callicrate Bander) to perform partial phallectomy in combination with a perineal urethrostomy (PU) has previously been described to be an effective and well-tolerated procedure in standing sedated horses.

Objectives
To share our experiences with the combined Callicrate Bander phallectomy (CBP) and PU (CBP/PU) focusing on potential complications, outcome and owner satisfaction.

Study design
Retrospective case series.

Methods
Medical records of 14 male equids that underwent CBP/PU at two different equine referral hospitals between 2012 and 2020 were reviewed. A long-term follow-up was conducted by telephone interview with the owners using a standardised questionnaire.

Results
Equids underwent CBP/PU to treat penile and preputial squamous cell carcinomas (11/14), equine sarcoids (2/14) and penile abscessation and paraphimosis after trauma (1/14). Early postoperative complications were mild and included transient post-urination haemorrhage, perineal or preputial oedema and partial dehiscence of the PU. Complications that required further veterinary care in the immediate postoperative period occurred in one animal, which had haemorrhage at the amputation site with subsequent haematoma and oedema formation, causing moderate signs of postoperative pain. Complications encountered after discharge from the clinic comprised transient urine leakage at the amputation site, transient purulent preputial discharge, abscessation of the penile remnant and urine staining of the hind legs, tail and/or perineum. Four equids were euthanased because of tumour recurrence.

Main limitations
Variable case details provided in the medical records and information regarding the postoperative healing process were mainly based on owner-assessment.

Conclusions
CBP/PU is a well-tolerated salvage procedure for male equids with debilitating conditions of the penis and prepuce. Severe postoperative complications are rare. If advanced stages of penile SCC are expected, careful case selection based on a rigorous preoperative examination is mandatory. Owner satisfaction with the postoperative result is high.

Clinical relevance

- The combination of a Callicrate Bander phallectomy and a perineal urethrostomy is well tolerated in equids and allows for the removal of penile and preputial tissues up to the level of the external preputial orifice in the standing animal.
- While transient mild postoperative complications at the amputation and perineal urethrostomy site are not infrequent, severe intra- and postoperative complications are rare.
- Owner acceptance and satisfaction with the combined Callicrate Bander phallectomy and perineal urethrostomy procedure is high, but owners must be aware that urine staining of the hind legs and perineum is a frequent consequence of the perineal urethrostomy that may require daily cleaning to prevent urine scalding.

EQUINE VETERINARY EDUCATION
Equine vet. Educ. (2022) **34** (12) 642
doi: 10.1111/eve.13611_1

Original Article

Environmental organic pollutants in hair samples from sport horses

O. Yavuz[†,*], H. H. Arslan[‡], O. Tokur[†], Z. Nuhoglu[†], O. Marangoz[†], S. Mushtaq[†], A. Arslan[§] and C. Ozdil[¶]

[†]Department of Pharmacology and Toxicology, Faculty of Veterinary Medicine, Ondokuz Mayis University; [‡]Department of Internal Medicine, Faculty of Veterinary Medicine, Ondokuz Mayis University, Samsun; [§]Jockey Club of Turkey, Ankara, Turkey; and [¶]Jockey Club of Turkey, Sanliurfa, Turkey
**Corresponding author e-mail: oguzhany@omu.edu.tr*

Keywords: horse; gas chromatography–mass spectrometry; hair; persistent organic pollutants; sport horses

Summary

Background
Previous studies have shown high levels of persistent organic pollutants (POPs) and their risks in humans and domestic animals, especially in cats and dogs. However, studies regarding the levels of POPs in horses are limited.

Objectives
To study the concentration of organochlorine pesticides (OCPs), polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs) and organophosphate pesticides (OPs) in hair samples collected from 52 sport horses in Turkey; and to investigate the possible relationship among current exposure situation, age, and sex of horses.

Study design
Original article.

Methods
Hair samples were collected from 52 sport horses, which were divided into three groups according to age: Group 1, <5 years (n = 17); Group 2, 5–10 years (n = 16); and Group 3, >10 years (n = 19). In addition to age, the samples were also analysed by location and sex. Thirty environmental pollutants (2 OPs, 7 OCPs, 15 PCBs and 6 PAHs) were analysed using a sensitive GC-MS method.

Results
All samples contained a minimum of one pollutant, and 23 of the 30 measured pollutants were identified in at least one sample. The number of positive samples and concentrations of POPs were higher in Group 2 and Group 3 than in Group 1 ($p < 0.05$). Females and males presented similar results. In terms of location, concentrations of almost all chemicals were higher in Sanliurfa than in Ankara ($p < 0.05$).

Main limitations
Feed, drinking water, and the other related environmental samples were not analysed to evaluate the relationship between those sources and POP levels in hair samples collected from sport horses.

Conclusions
The concentration of POPs in the hair and other tissues of sport horses should be monitored periodically. To the best of our knowledge, this is the first report to investigate levels of the POPs in hair samples from sport horses in Turkey.

Clinical relevance

- The presence of POPs in animals could be a causative factor in a variety of diseases, including cancer, metabolic disorders, immune suppression, growth failures, cardiovascular diseases and congenital abnormalities, even at very low concentrations.
- In the present study, the levels of POPs in horsehair were generally higher than previous studies conducted in humans and other animals. These findings may indicate the extent of environmental contamination and the importance of POPs as an external factor responsible for health problems in sport horses.
- In future, determining any relationships between the levels of POPs in biological fluids and race performance of sport horses could be worthwhile.

Complete Joint Support

To Maintain Soundness & Longevity

Overall Wellness

A wellness formula with all the benefits of Platinum Performance® Equine, designed to support your patient from head to hoof.

Research

More than 30 veterinary research projects have supported the effectiveness and development of Platinum formulas.

100% Quality

We choose quality and efficacy over low-cost ingredients, ensuring formula protection, potency and purity.

Advanced Joint Support

Includes a powerful combination of ingredients to support healthy cartilage, joint lubrication and a normal inflammatory response for joint longevity.

Show Safe

All formulas are subjected to extensive testing for over 200 banned substances for horse safety and athlete protection.

Results

Developed by veterinarians in clinical practice, to ensure results in horses from Olympic contenders to pet ponies.

Platinum Colic Coverage™ Eligible

Platinum Performance® CJ The Only Formula of Its Kind

As the most comprehensive combination of joint supporting ingredients available, Platinum Performance® CJ contains omega-3 fatty acids, ASU (Avocado/Soy Unsaponifiables), HA (Hyaluronic Acid), cetyl myristoleate, MSM, Boswellia serrata and more to help maintain soundness.

Platinum formulas are only available from your veterinarian or direct from Platinum Performance®.

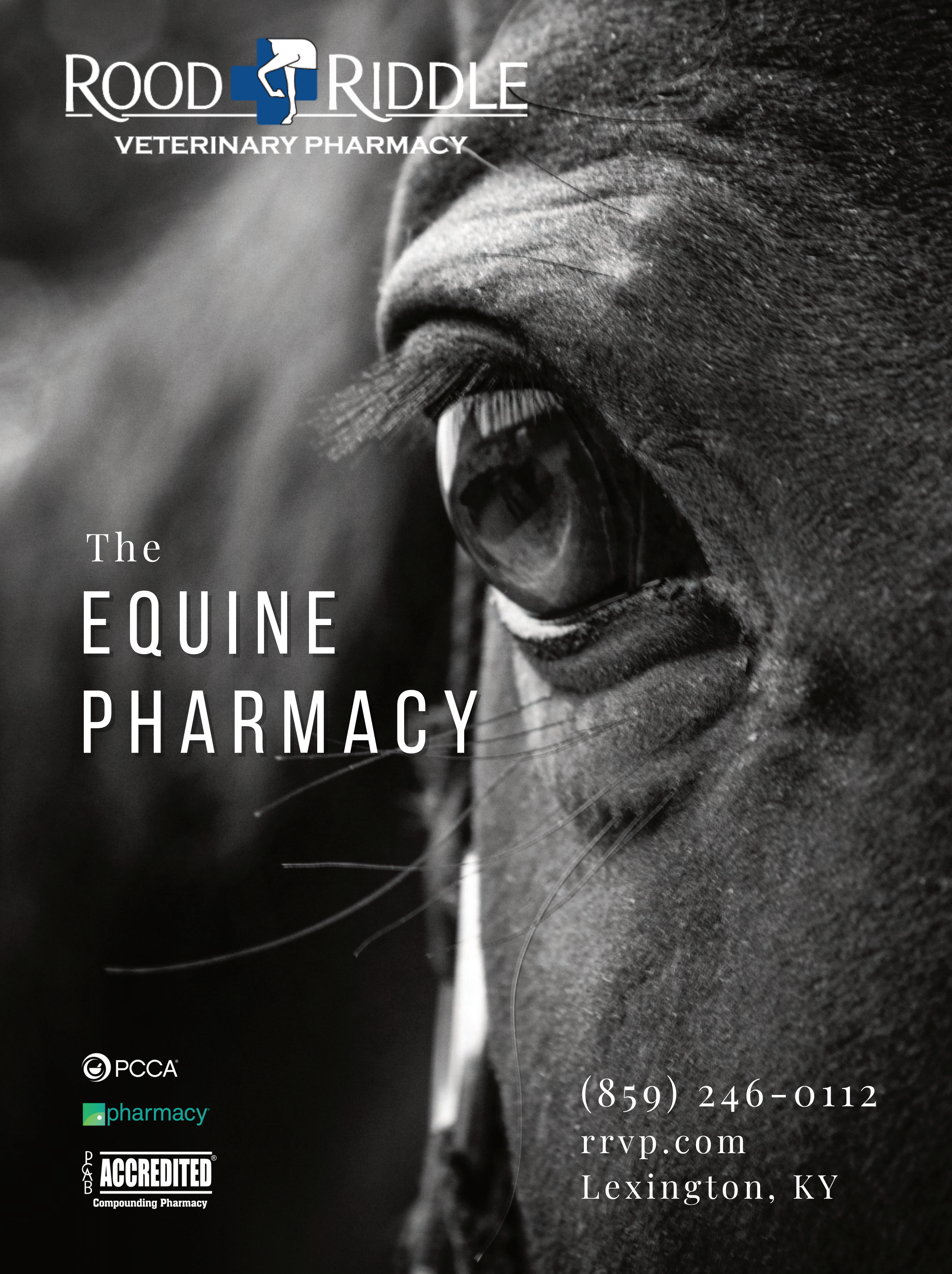
Recommended for:

- Performance horses and prospects
- Horses with joint health needs
- Horses with soft tissue concerns
- Senior horses

PLATINUM PERFORMANCE®

IT STARTS WITHIN®

PlatinumPerformance.com
866-553-2400


ROOD RIDDLE
VETERINARY PHARMACY
The
EQUINE
PHARMACY
PCCA
pharmacy
PCAB ACCREDITED
Compounding Pharmacy
(859) 246-0112
rrvp.com
Lexington, KY

Equine vet. Educ. (2022) **34** (12) 643
doi: 10.1111/eve.13616_1

Original Article

Effect of an oral supplement containing curcumin extract (Longvida®) on lameness due to osteoarthritis and gastric ulcer scores

F. M. Andrews[†,*], L. M. Riggs[†], M. J. Lopez[†], M. L. Keowen[†], F. Garza Jr.[†], C. Takawira[†], C.-C. Liu[†], Y. Liu[‡], N. P. Seeram[‡], A. Cairy[§] and M. St. Blanc[†]

[†]*Equine Health Studies Program, Department of Veterinary Clinical Sciences, School of Veterinary Medicine, Louisiana State University, Baton Rouge, Louisiana;* [‡]*Bioactive Botanical Research Laboratory, Department of Biomedical and Pharmaceutical Sciences, College of Pharmacy, University of Rhode Island, Kingston, Rhode Island; and* [§]*W.F. Young, Inc, East Longmeadow, Massachusetts, USA*
**Corresponding author email: fandrews@lsu.edu*

Keywords: horse; curcumin; equine gastric ulcer syndrome (EGUS); lameness; nonsteroidal anti-inflammatory drugs (NSAIDs)

Summary

Background
Herbal supplements containing curcumin and other ingredients are used for pain management in horses with osteoarthritis (OA).

Objectives
To test the effects of a herbal supplement containing curcumin and other ingredients in horses with lameness due to naturally occurring OA.

Study design
Two-period randomised crossover design.

Methods
Ten Thoroughbreds with naturally occurring chronic OA were randomly assigned to the treatment (BLP; Buteless® Performance) or control (CTR, no supplement) groups and fed daily for 30 days. On Days -1 (before treatment), 15 and 30, lameness examination, range of motion, pain on palpation and force platform data were collected. Plasma curcumin concentration and its metabolites were measured on Days 1 and 14. Gastroscopy, a complete blood count (CBC) and a serum biochemistry panel were performed on each horse before treatment on Day -1 and Day 31. Gastric lesions (ulcers) were scored in real time by a masked investigator.

Results
Mean peak vertical force (PVF), measured by the force platform, significantly increased in the lame limb of the BLP-treated horses on Days 15 (0.40 ± 0.13 N/Kg, $p = 0.0025$) and 30 (0.63 ± 0.14 N/Kg, $p < 0.0001$) compared with the CTR group. In addition, the mean normalised PVF was higher in the BLP group on Day 15 ($p = 0.0438$) and on Day 30 ($p = 0.0003$) when compared to CTR horses for the same days. The PVF significantly improved (≥5%; range, 5.2% to 33%) in 6 of 9 individual BLP-treated horses and did not improve (<5%; range, 0 to 3.4%) in 3 of 9 BLP-treated horses. Also, PVF improved (≥5%; range, 7.6% to 15.4%) in 3 of 9 horses in the CRT group. Squamous gastric lesion scores significantly decreased in both groups by Day 31. Plasma curcumin-O-sulfate concentrations (1.2 to 3.3 ng/ml) were present in 9 of 10 BLP-treated horses by Day 14.

Main limitations
Small sample size and the absence of a positive treatment (NSAID) control.

Conclusion
The BLP supplement containing curcumin achieved plasma concentrations and improved weightbearing in some treated horses with naturally occurring OA.

Clinical relevance

- A supplement containing curcumin and other ingredients fed daily for 30 days improved weightbearing in some of the horses with osteoarthritis by Days 15 and 30 of administration.
- Curcumin or other ingredients within the supplement did not cause or worsen nonglandular gastric ulcers.
- Curcumin and its metabolite (curcumin-O-sulfate, desmethoxycurcumin) were not present in plasma 2 hours after feeding on Day 1; however, plasma concentrations were found in 9/10 horses after feeding the supplement on Day 14.

EQUINE VETERINARY EDUCATION
Equine vet. Educ. (2022) **34** (12) 644-659
doi: 10.1111/eve.13581

Review Article

Monitoring techniques for equine anaesthesia

***C. Dagnall*[†,*], *L. Khenissi*[‡] *and E. Love*[†]**

[†]*Faculty of Health Sciences, The University of Bristol, Bristol, UK; and* [‡]*Langford Vets, Bristol, UK*
**Corresponding author email: cd9020@bristol.ac.uk*

Keywords: horse; anaesthesia monitoring; anaesthetic plane; cardiorespiratory monitoring; neuromuscular blockade monitoring

Summary

The anaesthetist aims to preserve normal physiology of the horse notwithstanding the use of general anaesthetic drugs and pre-existing pathological changes. Provision of analgesia and maintaining an adequate plane of anaesthesia are important alongside monitoring cardiorespiratory performance, response to noxious stimuli and temperature. There are a variety of techniques that subjectively or objectively assess physiological variables, and the results should be interpreted in the context of the anaesthetic protocol. Basic 'hands-on' monitoring of anaesthesia requires no equipment and is a core skill for every anaesthetist. However, as technology advances, many more electronic monitoring options have become available. This review describes how to use specific monitoring techniques, discusses the evidence underpinning them and evaluates their place in clinical practice. Where appropriate, normal and abnormal values are highlighted, although evaluation of trends may be more important in some cases. Regular documentation of variables enables trends to be identified and is key to appropriate early intervention. All basic monitoring techniques that require no equipment, such as ocular and mucous membrane assessment and pulse palpation, are recommended for every general anaesthetic procedure. The use of capnography, pulse oximetry, electrocardiography and blood pressure monitoring devices is recommended where indicated (Martinez et al., 2008), recognising that anaesthesia in horses is performed in a variety of places with different facilities and using various drug combinations.

Introduction

The anaesthetist aims to preserve normal physiology of the horse notwithstanding the use of general anaesthetic drugs and pathological changes. An adequate plane of anaesthesia and appropriate analgesia are important to facilitate the procedure being performed. Continuous patient assessment must be carried out to achieve this, with documentation of parameters at least every 5 minutes. A knowledge of what parameters to monitor and how to monitor them is essential, along with rapid interpretation.

Anaesthetic mortality in horses is relatively high with rates up to 1.9% (Johnston et al., 2002; Bidwell et al., 2007; Senior et al., 2007; Jago et al., 2015; Dugdale and Taylor, 2016; Nicolaisen et al., 2022). The Confidential Enquiry into Perioperative Equine Fatalities 4 (CEPEF 4) has recently been launched and, in due course, will provide data relating to current anaesthetic practices in horses (Gozalo-Marcilla et al., 2020). It is timely to revisit and discuss anaesthetic monitoring because of perceived high mortality rates.

Plane of anaesthesia

The concepts of stages and planes of anaesthesia originate from Guedel's classification, which characterises the continuum of anaesthetic depth in humans when administering ether (Guedel, 1927). Anaesthetic practice has since advanced dramatically, yet reference to the plane of anaesthesia remains relevant during patient monitoring. Maintaining an adequate plane of general anaesthesia in horses is essential for safety and welfare reasons. This is primarily achieved through 'hands-on' clinical evaluation of the animal although objective measurement using electroencephalography (EEG) and bispectral index (BIS) has been investigated (see 'Electroencephalography'). The adverse effects of awareness are well documented in humans (Kotsovolis & Komninos, 2009) though conversely, relative overdoses of anaesthetic agent are also undesirable and can significantly compromise cardiovascular and respiratory function as well as contributing to anaesthetic related morbidity and mortality.

Reflexes and patient characteristics

Observation of ocular movements and reflexes are monitored in most equine anaesthetic procedures (Hubbell et al., 2010). Observation is quick and easy except when surgical access to the head is required. The palpebral reflex is triggered by stroking the cilia although if performed repeatedly this reflex will fatigue. The corneal reflex is elicited by corneal pressure though may risk corneal damage so routine evaluation is not recommended.

Commonly used drugs influence the consistency of ocular observations that indicate the plane of anaesthesia (Taylor & Clarke, 2007a; Trim, 1998). Ketamine produces spontaneous blinking, a brisk palpebral reflex and some nystagmus with a variable eye position (Trim, 1998). In contrast, nystagmus during anaesthesia with volatile agents is indicative of insufficient anaesthetic plane and ocular reflexes become slower as the plane of anaesthesia deepens (Taylor & Clarke, 2007b). Absence of a corneal reflex and/or a central dry eye with any drug protocol should raise concern of overdose of anaesthetic agent (Hubbell & Muir, 2009; Taylor & Clarke, 2007b). Most anaesthetic and sedative agents reduce tear production (Brightman et al., 1983; Leonardi et al., 2020), and administration of artificial ocular lubrication will assist with corneal protection.

Other indicators of anaesthetic plane include the anal reflex. A reduction in anal contraction on stimulation is associated with increasing anaesthetic plane (Hubbell & Muir, 2009). Shivering and increased muscle tension (particularly noticeable in the neck and legs if the horse is in dorsal recumbency) are often useful indicators of an inadequate plane of anaesthesia for surgical stimulus, although impending conscious or unconscious movement remains challenging to predict. Monitoring reflexes and patient characteristics using a 'hand-on' approach is a crucial and fundamental skill for the equine anaesthetist in both 'field' and hospital settings.

Cardiovascular performance and oxygenation

Adequate tissue perfusion is important for ensuring oxygen delivery to the tissues. The driving force for tissue perfusion is the mean arterial pressure (MAP), which is a product of cardiac output (CO) and total peripheral resistance. Cardiac output can be defined as the product of stroke volume (SV) and heart rate (HR), and the SV depends upon the afterload, preload and cardiac contractility. Objective measurements of perfusion of tissues such as the gastrointestinal tract and muscle are possible with spectrophotometry (Reichert et al., 2014), surface oximetry (Snyder et al., 1994) and LASER Doppler flowmetry (Edner et al., 2005). However, their use is currently limited to research work and further work is required to establish their clinical utility in practice.

Maintaining delivery of oxygen to tissues is critical for aerobic respiration and long-term tissue survival. **Fig 1** demonstrates the dependence of oxygen delivery on both cardiovascular function and oxygen transfer, the latter of which also depends on ventilation (see 'Ventilation'). Oxygen delivery (DO_2) is calculated by:

$$DO_2 = CaO_2 \times CO.$$

Where CaO_2 = arterial blood oxygen content. CaO_2 is the amount of oxygen carried per 100 ml of arterial blood, representing the sum of the oxygen bound to haemoglobin and dissolved in blood. Compromised cardiopulmonary function during anaesthesia caused by hypoventilation, ventilation-perfusion mismatching and shunt formation is likely responsible for intraoperative hypoxaemia (Bardell et al., 2020; Day et al., 1995; Hall et al., 1968; Nyman & Hedenstierna, 1989).

Hypoxaemia is defined as an arterial partial pressure of oxygen (PaO_2) < 8.0 kPa (60 mmHg), although values < 10.7 kPa (80 mmHg) are considered suboptimal (Pascoe et al., 1983). Hypoxaemia is challenging to rectify during equine general anaesthesia (Auckburally & Nyman, 2017; Nyman et al., 2012; Trim & Wan, 1990), although the resultant negative effects are unclear (Trim & Wan, 1990).

Haemoglobin saturation in arterial blood (SaO_2) depends on the PaO_2, as illustrated by the oxy-haemoglobin dissociation curve. This curve is shifted to the left for horses compared to humans, meaning equine haemoglobin is 50% saturated at a PaO_2 of approximately 3.3 kPa (25 mmHg) whereas human haemoglobin requires a PaO_2 of 3.6 kPa (27 mmHg) for 50% haemoglobin saturation (Cambier et al., 2005; Clerbaux et al., 1986). The clinical relevance of this 0.3 kPa (2 mmHg) difference is unclear.

The most common cause of fatality associated with anaesthesia in noncolic cases is reported as cardiovascular collapse, followed by fractures (Johnston et al., 2002). Poor perfusion resulting from nonfatal cardiovascular compromise is linked to the development of myopathy (Grandy et al., 1987) which contributes to weakness in recovery. This may increase the likelihood of fractures. Thorough evaluation of the cardiovascular system during anaesthesia is essential to reduce associated morbidity and mortality.

Basic cardiovascular monitoring

Mucous membranes can be evaluated to subjectively assess tissue perfusion. Both sluggish capillary refill times (over 2 s) and pale pink or greyish colouration (sometimes seen with halothane) may indicate poor perfusion from either reduced CO or vasoconstriction which is common after alpha-2 agonist administration (Taylor & Clarke, 2007b). Congested or bright red mucous membranes can be secondary to

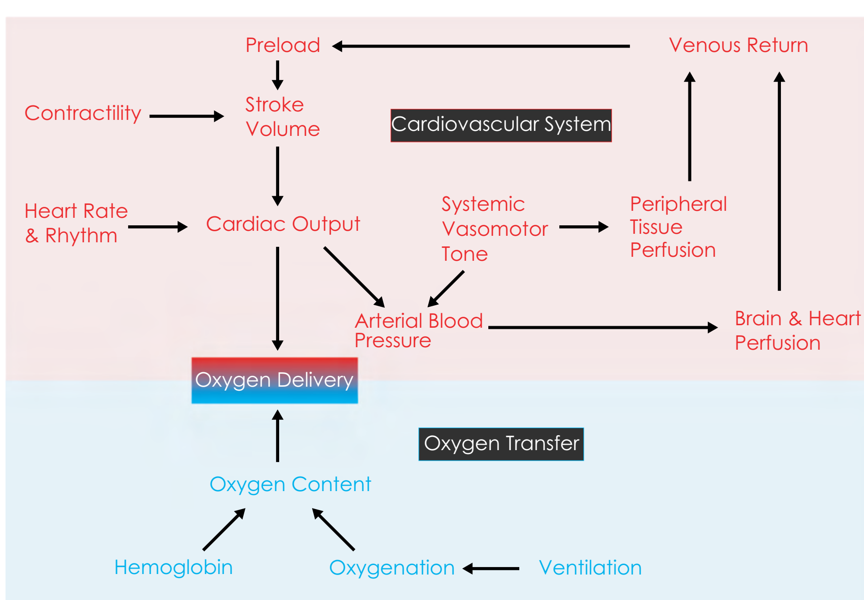


***Fig 1:** Interplay of cardiovascular function and oxygen transfer required to achieve oxygen delivery to the tissues (modified from Haskins (2015), Figs 1 and 4).*

vasodilation. This is occasionally seen with hypercapnia but, more commonly, in cases of septic shock. Congested mucous membranes can also be appreciated with over-zealous dobutamine administration resulting in increased cardiac output and possible vasodilation. Visual evaluation of mucous membrane colour is a poor indicator of haemoglobin desaturation, with observers failing to identify cyanosis in humans with saturations of <75% (Medd et al., 1959). Anaemia further impedes visual assessment. Mucous membrane colour should not be relied upon for assessment of oxygenation status and rather, used as a prompt for further investigation. Objective measurements of oxygenation status (e.g. pulse oximetry, arterial blood gas (ABG) analysis) will yield more accurate results and help guide anaesthetic management.

The pulse rate can be measured by peripheral pulse palpation, and although this can identify irregularities in rhythm, additional objective monitoring (e.g. electrocardiogram [ECG]) is recommended. The normal HR for anaesthetised horses is 30–45 beats/min, but 35-60 beats/min should be expected in anaesthetised foals (Hubbell & Muir, 2009), as their resting heart rate is 100 beats/min at birth (Robertson, 2005). Pulse quality can provide an indication of pulse pressure, which represents the difference between systolic (SAP) and diastolic arterial pressure (DAP). However, there is no evidence to suggest whether palpation of peripheral pulses provides an accurate assessment of pulse pressure in horses. Pulse pressure is further discussed in 'Invasive Blood Pressure Measurement'. Objective measurement of blood pressure alongside integration with other parameters such as HR is recommended if there is concern about abnormal pulse quality or for prolonged general anaesthesia.

Pulse oximetry

The pulse oximeter provides continuous estimation of the SaO_2 (SpO_2). Values of 93% approximate to a PaO_2 = 8.0 kPa (60 mmHg) in horses (Cambier et al., 2005; Smale et al., 1994), so the anaesthetist should strive for SpO_2 values equal to or above this. Pulse oximetry also indicates the presence of pulsatile flow to tissues and displays the pulse rate. Devices also have the advantage of providing a continuous audible output which is often accompanied by a pitch change, warning of decreasing SpO_2. The device is noninvasive, and its portable nature makes it useful for field anaesthesia. Patient contact is made with a cutaneous or muco-cutaneous probe/clip often placed on the tongue or lip. There are a variety of clips (**Fig 2**) with the larger sizes more suitable for equine use. There is no consistently reported superior location (Chaffin et al., 1996; Giguère et al., 2014).

Oxy-haemoglobin and deoxy-haemoglobin are differentially detected using infra-red and near infra-red radiation (wavelengths 660 nm and 940 nm respectively). Radiation is emitted from two light emitting diodes embedded within the probe and either transmitted through or reflected off tissues to a photodiode detector. The infra-red radiation is predominantly absorbed by oxy-haemoglobin and near infra-red by deoxy-haemoglobin. The ratio of infra-red and near infra-red absorption is used to calculate the SpO_2 based on an experimental calibration curve, where SaO_2 was measured in healthy human volunteers (Kelleher, 1989).

The gold standard of arterial oxygenation measurement is ABG analysis, but the benefit of continuous monitoring with pulse oximetry should not be underestimated. However, the device also has limitations. Devices are reliable for tracking changes in equine SaO_2 but tend towards inaccuracy as SaO_2 drops below 90% (Chaffin et al., 1996; Koenig et al., 2003; Martinez et al., 1999; Matthews et al., 1994; Zoff et al., 2019). They also depend on pulsatile flow in the arteries, so any disruption in perfusion or venous pulsations will limit device accuracy. Other molecules absorbing near infra-red or infra-red wavelengths also cause spurious SpO_2 readings. For example, methaemoglobin absorbs red and infra-red radiation equally well, resulting in an SpO_2 ~ 85% (Chan et al., 2013). Although pulse oximetry can detect hypoxaemia, there is a time delay between this and the initiation of hypoxic event. Oxygen analysers may be able to warn of this risk prior to patient insult if an inadequate fraction of inspired oxygen (FiO_2) is administered. This is because they sample the inspired gas from the breathing circuit (see 'Fraction of Inspired Oxygen Analysers').

The electrocardiogram

The depolarisation and repolarisation of a large mass of cardiac myocytes that occurs during the spread of electrical impulses through the cardiac muscle can be detected and amplified at the surface of the skin. A minimum of three electrode contact points with crocodile clips or adhesive gel electrodes can be configured in a 'base–apex orientation' if access to the left and right of the horse is possible (**Fig 3a**) (Mitchell, 2019), although any orientation of pairs of electrodes will produce a waveform if they span the heart (Taylor & Clarke, 2007b). Electrode contact can be enhanced using isopropyl alcohol or additional gel depending on electrode type to improve trace quality. The potential difference is measured between paired electrodes referred to as 'leads' (**Fig 3b**). Waves of depolarisation that travel towards the positive electrode result in an upward deflection and waves that travel away result in a downward deflection on the ECG trace producing the characteristic waveform shown in **Fig 3c** (Mitchell, 2019). The normal electrical path of the wave of depolarisation begins at the sinus node, spreading through the atria then the atrioventricular node. From here, the wave is directed via the Bundle of His and then throughout the ventricular myocardium via Purkinji fibres. Additional waveforms that may or may not be present in the equine ECG include the T_a waveform which is a deflection after the P wave representing atrial repolarisation and the U wave which follows the T wave. The source of the U wave may represent Purkinji fibre repolarisation (**Fig 3c**).

Heart rate variability describes the variable duration of the R intervals of the ECG governed by the autonomic nervous system. It represents an emerging field of equine monitoring which may assist in postoperative prognostic assessment (McConachie et al., 2016).

Noninvasive blood pressure

The minimum acceptable value for blood pressure during equine anaesthesia is controversial. Deleterious effects of maintaining MAP > 60 mmHg have not been demonstrated (Duke et al., 2006; Franci et al., 2006) yet maintaining

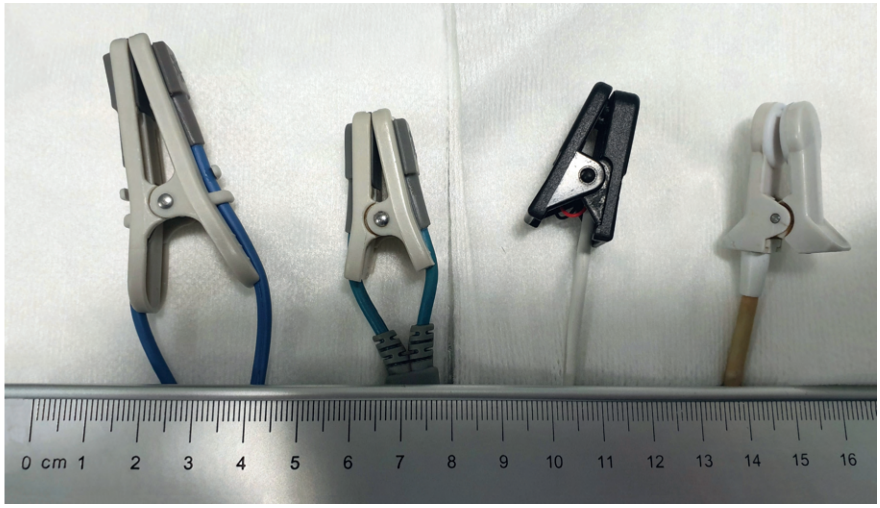


Fig 2:* *Pulse oximetry clips of varying design and size. Larger sizes are usually more appropriate for equine use.

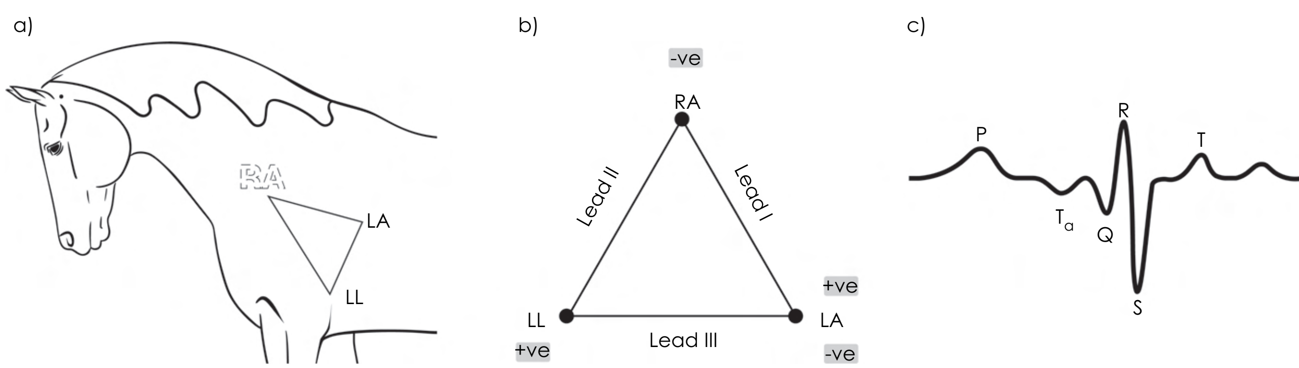


Fig 3:* *Equine electrocardiogram; (a) electrode placement in the base–apex orientation, dashed line RA on the right and solid line LL and LA on the left of the horse; (b) Einthoven's triangle; (c) lead I trace; RA right arm; LA left arm; LL left leg; +ve positive electrode; -ve negative electrode; P atrial depolarisation; T_a atrial repolarisation (not always present); QRS ventricular depolarisation; T ventricular repolarisation; U possible purkinji repolarisation (not always present).

MAP > 70 mmHg may be beneficial in avoiding or reducing the severity of postanaesthetic myopathy which may be caused by reduced tissue perfusion (Duke et al., 2006; Peek, 1993).

Noninvasive blood pressure measurement (NIBP) can be performed using oscillometry. An inflatable cuff that is one fifth of the tail circumference is placed over the middle coccygeal artery in adult horses and foals (Gent et al., 2015; Giguère et al., 2005; Latshaw et al., 1979; Nout et al., 2002; Tearney et al., 2016). Cuff placement over the dorsal metatarsal artery is also acceptable in anaesthetised foals when using the Cardell Veterinary Monitor 9402 (CAS Medical Systems) and Dinamap Pro 100 (GE Medical Systems) (Giguère et al., 2005). The cuff inflates until arterial flow is occluded and then gradually deflated until arterial flow resumes, giving the SAP (Haskins, 2015). MAP corresponds to the maximum of the pulsations and DAP when the pulsations decrease (Haskins, 2015). Detection of pulsations is via a pressure sensor within the cuff. An alternative pulsation detection method is a Doppler probe placed distal to the cuff over the artery.

NIBP devices have been compared to invasive blood pressure (IBP) monitoring which is considered the gold standard for monitoring blood pressure. There is much variability in NIBP device performance which could result in inappropriate management of hypotension (Branson, 1997; Hatz et al., 2015; Rousseau-Blass et al., 2020). Their reliability is questionable in hyper- and hypotensive states in adult anaesthetised horses (Tünsmeyer et al., 2015). NIBP lacks beat-to-beat monitoring but provides a noninvasive option of trend assessment (Heliczer et al., 2016). Inappropriately large or small cuffs can cause incorrect systematically low or high readings, respectively, (Latshaw et al., 1979) and the differing cuff sizes used in various studies complicate the interpretation of results (Gent et al., 2015; Tearney et al., 2016).

Invasive blood pressure

Arterial catheterisation is required for IBP measurement. Strict asepsis should be practised for catheter placement and the transducer set-up to avoid infection, as consequences can be catastrophic (Barr et al., 2005). Facial artery catheterisation may yield more reliable blood pressure measurements than metatarsal artery catheterisation as it is a more central artery (Gent et al., 2015). Furthermore, amplification of the pulse wave occurs towards the periphery causes overestimation of the systolic pressures (Gent et al., 2015; Muir et al., 1983). The catheter is connected to a column of pressurised fluid and a transducer. Most pressure transducers comprise of one or two diaphragms that are exposed to pressure changes within the fluid column because of arterial pulsations. A 'fast flush' lever or pull system is usually located near the pressure transducer (**Fig 4a**). Strain gauges transduce this pressure change into an electrical signal which is digital depiction of an arterial pressure wave (**Fig 4b**) (Walton & Wilson, 2017). Prior to use, equipment should be inspected for damage (Chevallier & Oostrom, 2020), the transducer placed at the level of the right atrium (Trim, 1998) and the system zeroed to atmospheric pressure.

The arterial waveform represents vascular distension in response to the ejection of the SV and therefore depends on the artery cannulated. Peripheral artery waveforms have an increased gradient on the systolic upstroke, a delayed or absent dichrotic notch and a more obvious, lower diastolic wave than their central counterpart (O'Rourke & Yaginuma, 1984). The dichrotic notch represents wave reflection from the closure of the aortic valve. Pulse pressure is the difference between systolic and diastolic pressure and depends upon SV and arterial compliance. It may give an indication of CO (Hubbell & Muir, 2009). Narrow pulse pressure can be a result of reduced SV or vasoconstriction. A reduced SV may manifest as hypotension and require intervention; however, vasoconstriction secondary to alpha-2 agonist administration may not and hypertension is common. Wide pulse pressure palpated as hyperdynamic pulses can indicate increased CO and vasodilatation, which is sometimes present in the early stages of septic shock. Hyperdynamic pulses may also be appreciated after dobutamine administration.

The pressurised fluid column used for IBP measurement will oscillate independent of any external energy input. The rate of the oscillations is described as the natural frequency. If the frequency of arterial blood flow oscillations approaches the fluid column's natural frequency, the waves summate in a phenomenon called resonance. To assess the degree of resonance within the system, a square wave test can be employed (**Fig 4c**). Damping is introduced to reduce resonance (Walton & Wilson, 2017). Under-damping results in an erroneously high SAP and jagged waveform (**Fig 4d**) and can be rectified by changing tubing so it has a slightly wider bore or more compliance to increase damping (Moxham, 2003). Over-damping results in erroneously low SAP, high DAP and a flattened waveform (**Fig 4e**). It can be caused by air bubbles, blood clots, narrow catheters or compliant tubing (Moxham, 2003). If a sudden loss of trace is experienced, check the patient still has a peripheral pulse and then

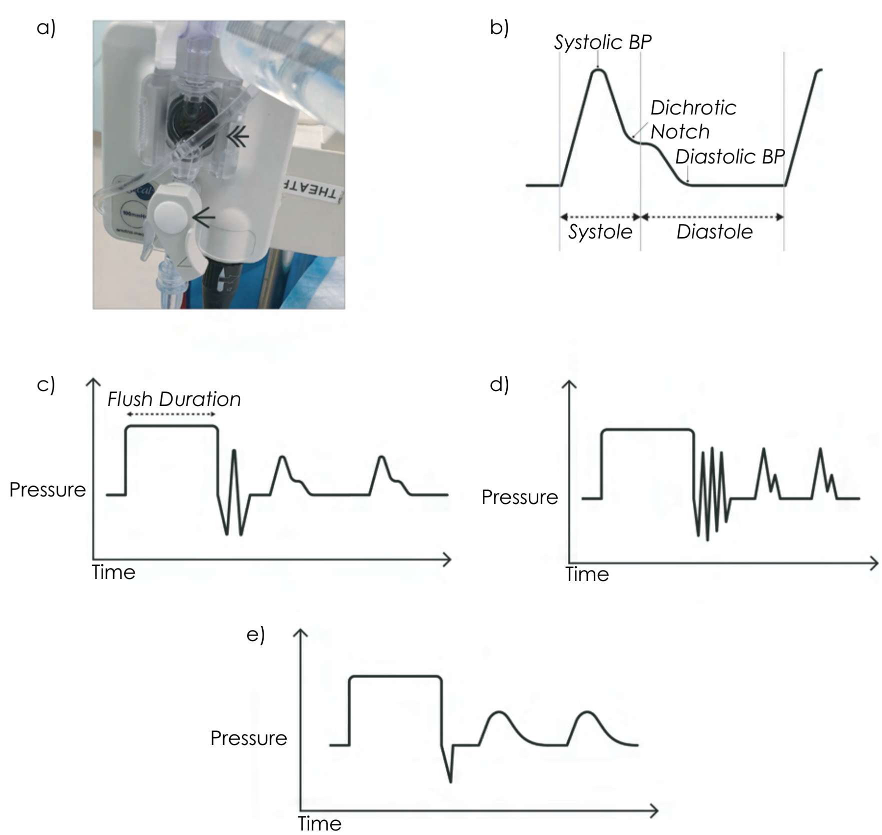


***Fig 4:** Invasive blood pressure trace; (a) fast flush switch (single arrowhead) located below the transducer (double arrowhead); (b) the invasive blood pressure trace; (c) optimal damping - 1-2 oscillations after the square wave; (d) under-damping - 2 or more oscillations after the square wave and jagged trace with greater amplitude; (e) over-damping - less than 1 oscillation after the square wave and smoothed trace with lower amplitude. BP, blood pressure.*

consider whether the arterial catheter is blocked or dislodged.

Urine production

Urinary catheters are placed during most equine anaesthetics in a theatre setting to minimise urine contamination in the operating theatre. They also enable monitoring of urine production and avoid excessive urination in the recovery box resulting in a wet, slippery floor. Alpha-2 agonists are commonly used as part of general anaesthetic protocols and increase urine production in horses (Gasthuys et al., 1996; Nuñez et al., 2004; Watson et al., 2002). This can manifest as a reduced circulating volume and should be considered when troubleshooting causes of hypotension.

Ventilation

Spontaneous ventilation is possible during equine anaesthesia, but recumbency and most anaesthetic drugs induce hypoventilation (Benson et al., 1982; Day et al., 1995; Sorenson & Robinson, 1980). Hypoventilation is defined as ventilation which is unable to match the metabolic rate of the body and is characterised by a rising partial pressure of arterial carbon dioxide ($PaCO_2$) (McDonell & Kerr, 2015). Normal $PaCO_2$ values for awake horses are 4.7 – 6 kPa (35–45 mmHg), and values greater than this are referred to as hypercapnia. Anaesthetised horses often have $PaCO_2$ values up to 8 kPa (60 mmHg) as a result of reduced minute ventilation, which can be due to either reduced TV, respiratory rate or both (McDonell & Kerr, 2015). A TV of 14–18 ml/kg in adult horses and 12-14 ml/kg in foals is recommended during mechanical ventilation (Hubbell, 2010). Along with the function of the cardiovascular system, ventilation plays a critical role in tissue oxygen delivery (**Fig 1**) (see 'Cardiovascular Performance and Oxygenation').

Basic monitoring of ventilation

Contrary to most mammals, adult horses have active and passive components to both inspiratory and expiratory phases (Koterba et al., 1985). Contraction of respiratory muscles assists the end of expiration and beginning of inspiration (Koterba et al., 1985), and these active phases of ventilation can become more pronounced during light planes of anaesthesia. They can also be observed as spontaneous ventilation attempts during mechanical ventilation if the plane of anaesthesia is light. In dorsal recumbency, upwards abdominal movements can be seen during inhalation, corresponding to the caudal movement of the dependent diaphragm (Mosing et al., 2017) and outwards chest wall movement. Similar diaphragmatic and thoracic excursions occur in lateral recumbency (Benson et al., 1982). It is not possible to estimate tidal volumes from visual assessment of thoracic excursion, but life-threatening patterns such as agonal breathing or marked airway obstruction can be identified along with patient–ventilator asynchrony. Counting respiratory rate from thoracic and abdominal movements, subjectively assessing effort and depth of ventilation by observing the patient and ventilator bellows or reservoir bag movements are examples of basic ventilation monitoring. Capnography and spirometry can provide an objective guide as to when to instigate and how to deliver mechanical ventilation.

Capnography and capnometry

Capnometry is the measurement of end tidal CO_2 partial pressure ($EtCO_2$) from the gases in the breathing circuit sampled close to the patient (**Fig 5**), and capnography produces a continuous waveform of CO_2 partial pressure (**Fig 6**). Measurement of $EtCO_2$ is useful when it provides a close estimation of $PaCO_2$ because it allows continuous monitoring. Hypercapnia produces detrimental and seemingly desirable effects, most of which are secondary to sympathetic stimulation (**Table 1**). It is these desirable effects that lead some authors to suggest moderate levels of hypercapnia can be tolerated (Hubbell & Muir, 2009; Moens, 2013).

Capnography can provide evidence that the circulatory system is capable of CO_2 transport as a fall in CO results in a reduced $EtCO_2$ when ventilation is constant. Capnography is also useful for confirming endotracheal intubation, identifies gas leakages and reveals abnormal ventilation patterns (**Fig 6**).

Marked differences between alveolar and arterial CO_2 partial pressures (A-a PCO_2) have been demonstrated during anaesthesia in horses, influenced by anaesthetic protocol, patient health status, bodyweight, ventilation strategy and recumbency (Geiser & Rohrbach, 1992; Koenig et al., 2003; Meyer & Short, 1985; Moens, 1989; Neto et al., 2000; Rainger et al., 2010). The A-a PCO_2 is likely a result of ventilation-perfusion mismatching, reflecting inefficient gas exchange (Mosing et al., 2018b). Intermittent $PaCO_2$ analysis alongside continuous $EtCO_2$ trend analysis represents a sensible

***Fig 5:** Gas sampling port at the 'Y' piece in the equine breathing circuit.*

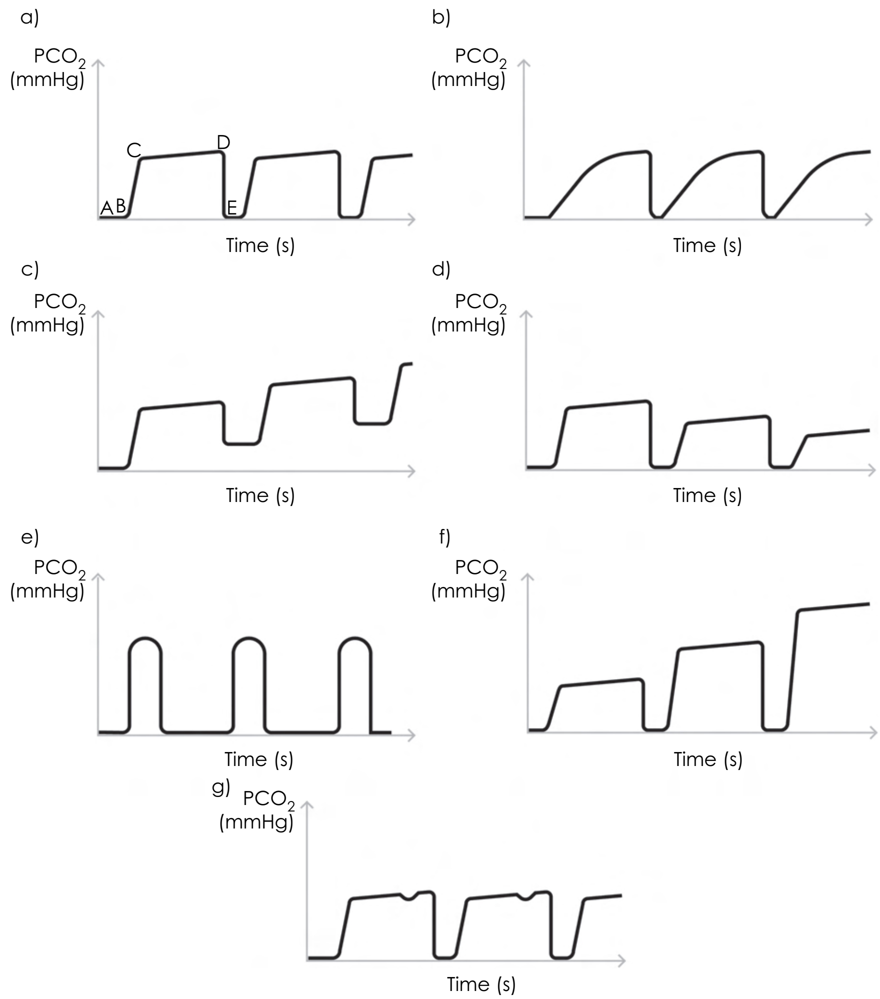


Fig 6: Capnography waveforms; (a) normal capnogram, a-b baseline, b-c beginning of expiration, C-D expiratory plateau, D point of end tidal carbon dioxide measurement, D-E inspiration; (b) expiratory obstruction; (c) rebreathing carbon dioxide; (d) hyperventilation; (e) leaking of expired gases; (f) hypoventilation; (g) curare cleft, spontaneous ventilation during mechanical ventilation.

monitoring strategy (see 'Blood Gas Analysis') (Ahn et al., 1997; Cribb, 1988; Geiser & Rohrbach, 1992; Koenig et al., 2003; Neto et al., 2000). The optimal frequency of $PaCO_2$ analysis has not been established because it is unclear if the A-a PCO_2 is influenced by the duration of anaesthesia (Ahn et al., 1997; Geiser & Rohrbach, 1992; Moens, 1989; Rainger et al., 2010).

Infra-red spectroscopy is commonly used to measure $EtCO_2$ in clinical practice. Most capnography monitors used for equine anaesthesia are side stream, as they sample gas from the breathing circuit close to the patient and analyse the sample distant from the patient. Mainstream capnographs analyse CO_2 concentrations directly within the breathing circuit. They are not usually suitable for equine anaesthesia as most connections are not compatible with the large diameter equine endotracheal tubes (Bednarski & Muir, 2009). Owing to the time taken for sampling and analysis, there is a slight delay in the $EtCO_2$ readings with side stream capnographs compared to the ventilation phase of the patient.

Additional expiratory gas analysis

Alveolar concentration of volatile agents

When general anaesthesia is maintained with volatile anaesthetics, measurement of the alveolar concentration of the volatile agent may assist in approximating anaesthetic plane, reducing the likelihood of inadvertent patient movement (Parviainen & Trim, 2000). In rebreathing systems, the vaporiser setting can be different to the volatile concentration within the breathing circuit (Trim, 1998) making gas analysers useful.

The minimum alveolar concentration (MAC) is defined as the minimum value of the end tidal volatile agent percentage that prevents movement in response to a nociceptive stimulus in 50% of patients (Merkel & Eger, 1963). The end tidal volatile agent percentage is assumed to be in equilibrium with the volatile concentration at the brain, which is their target site. This enables a quantitative measure of the plane of anaesthesia achieved with volatile agents compared to that described by Guedel (1927). MAC values

TABLE 1: Advantages and disadvantages of hypercapnia during general anaesthesia in horses

Disadvantages	Advantages
Summative effect on decreasing pH if metabolic acidaemia is present (Moens, 2013).	Maintenance of cerebral perfusion pressure during anaesthesia (Brosnan et al., 2003).
The reduced minute volume that results in hypercapnia may impair the uptake of volatile agent, risking patient movement (Trim, 1998).	Increase in cardiac index and blood pressure ($PaCO_2$ > 7.3 kPa (55 mmhg)) (Khanna et al., 1995).
Decreased PaO_2 (Thompson & Bardell, 2016).	Reduce the time to spontaneous ventilation when mechanical ventilation is discontinued ($PaCO_2$ ˜ 8.0 kPa (60 mmHg)) (Thompson & Bardell, 2016).
Enhance the effects of anaesthetic agents risking overdose ($PaCO_2$ > 12.5 (93 mmHg) kPa) (Eisele et al., 1967).	Allows for reduced mechanical ventilation, circumventing its negative cardiovascular effects (Hubbell & Muir, 2009; Moens, 2013).

for volatile anaesthetics in adult horses are shown in **Table 2** although variable concentrations may be required depending on: adjunctive drugs administered; age; physiological state of the patient (Brosnan, 2013); and atmospheric pressure. Foals generally have a reduced MAC compared to adult horses, although there is limited literature demonstrating this. For example, the MAC for isoflurane in foals is approximately 0.84% (Dunlop et al., 1989), whereas in adult horses it is approximately 1.3% (Steffey et al., 1977) (**Table 2**). It should be noted that market authorisations for use of volatile agents vary depending on country.

Most modern anaesthetic monitors quantify volatile anaesthetic agent concentration from gas samples from the breathing circuit (**Fig 5**) and analyse them using infra-red absorption spectroscopy. Molecules absorb radiation at varying wavelengths, allowing differentiation between various volatile anaesthetic agents. The absorbance peaks of different anaesthetic agents vary between 3 and 13 μm, but there is overlap within this range (Anaesthesia Gas Monitoring: Evolution of a de facto Standard of Care, 2009; Seavell, 2005). The light absorption is proportional to the gas concentration, obeying the Beer–Lambert Law:

$$A = \varepsilon l C.$$

Where A = absorption, ε = molar extraction coefficient, l = optical path length and C = concentration.

TABLE 2: Minimum alveolar concentration values of volatile agents for horses

Volatile Anaesthetic	MAC (%) for Adult Horses
Halothane	0.9 (Steffey et al., 1977)
Isoflurane	1.3 (Steffey et al., 1977)
Sevoflurane	2.3% (Aida et al., 1994) 2.84% (Steffey et al., 2005)
Desflurane	7.6% (Tendillo et al., 1997)

Methane absorbs light at 3.3 μm and is excreted via the lungs in horses (Sasaki et al., 1999). Infra-red analysers, such as the Datex Capnomac Ultima (Datex Instrumentarium Corp.), that utilise the lower end of the absorption spectra for volatile agents are subject to interference from methane (Dujardin et al., 2005; Moens et al., 1991; Turner et al., 2008). This renders their output value for end tidal volatile concentration erroneously increased for halothane and decreased for isoflurane and sevoflurane (Dujardin et al., 2005; Moens et al., 1991; Turner et al., 2008). Photoacoustic infra-red analysers (e.g. Hewlett Packard M 1025 B, Philips Nederland BV) utilise pulsed wavelengths of 10.3–13 μm and can circumvent this problem (Dujardin et al., 2005; Walder et al., 1993).

Fraction of inspired oxygen analysers

Hypoxaemia in anaesthetised horses can occur despite using 100% oxygen as a carrier gas (Hall et al., 1968). Lowering the FiO_2 is not recommended as it may not reduce absorption atelectasis during anaesthesia in mechanically ventilated horses (Taylor & Seymour, 2016) and reduces muscle oxygenation (Portier et al., 2009). Absorption atelectasis is the collapse of alveoli secondary to rapid diffusion of oxygen into the pulmonary capillaries, leaving no gas remaining within the alveoli to assist in keeping them inflated. Monitoring FiO_2 allows confirmation the percentage of oxygen in the breathing circuit (**Fig 7**) and is performed by analysing gas samples close to the endotracheal tube (**Fig 5**). Low FiO_2 values can result from low flow rates (e.g. if there is inadequate de-nitrogenation of breathing circuits, or leaking equipment) or dysfunction of gas delivery (Otteni, 1993). Oxygen analysers can alert the anaesthetist to low oxygen percentages in the breathing circuit, yielding the potential to avoid hypoxaemic insult. Modern gas oxygen analysers utilise the paramagnetic properties of oxygen. An electromagnetic field generates a pressure difference between the sample gas and a reference gas, depending on the sample gas oxygen concentration (Langton & Hutton, 2009). This is detected by a transducer and converted into an electrical signal. Analysers must contain a water trap as water vapour can cause erroneous readings (Garg & Gupta, 2013). Fuel cells can also be used and are like the Clark electrode (See ‘Blood Gas Analysis’), except the reaction of oxygen with the lead anode generates the electrical current (Garg & Gupta, 2013). Fuel cells should be replaced regularly as the lead is oxidised but are not vulnerable to water vapour interference.

Temperature

In humans, hypothermia increases surgical site infections, intraoperative blood loss (Xu et al., 2020) and cardiac complications (Frank et al., 1997) and impairs immunological function (Qadan et al., 2009). Adverse effects of hypothermia in horses are unclear, although it may prolong recovery times and increase the number of attempts to stand (Mayerhofer et al., 2005; Voulgaris & Hofmeister, 2009). It is logical to maintain normothermia (36.5 – 38°C) to preserve normal physiological function (Hubbell & Muir, 2009). Factors contributing to hypothermia during anaesthesia include environmental conditions, duration of anaesthesia, wetting of the patient (e.g. surgical preparation, profuse sweating) and contact with cold surfaces (Mayerhofer et al., 2005; Tomasic, 1999). Direct measurement of core body temperature by cannulation of the pulmonary artery is reserved for clinical

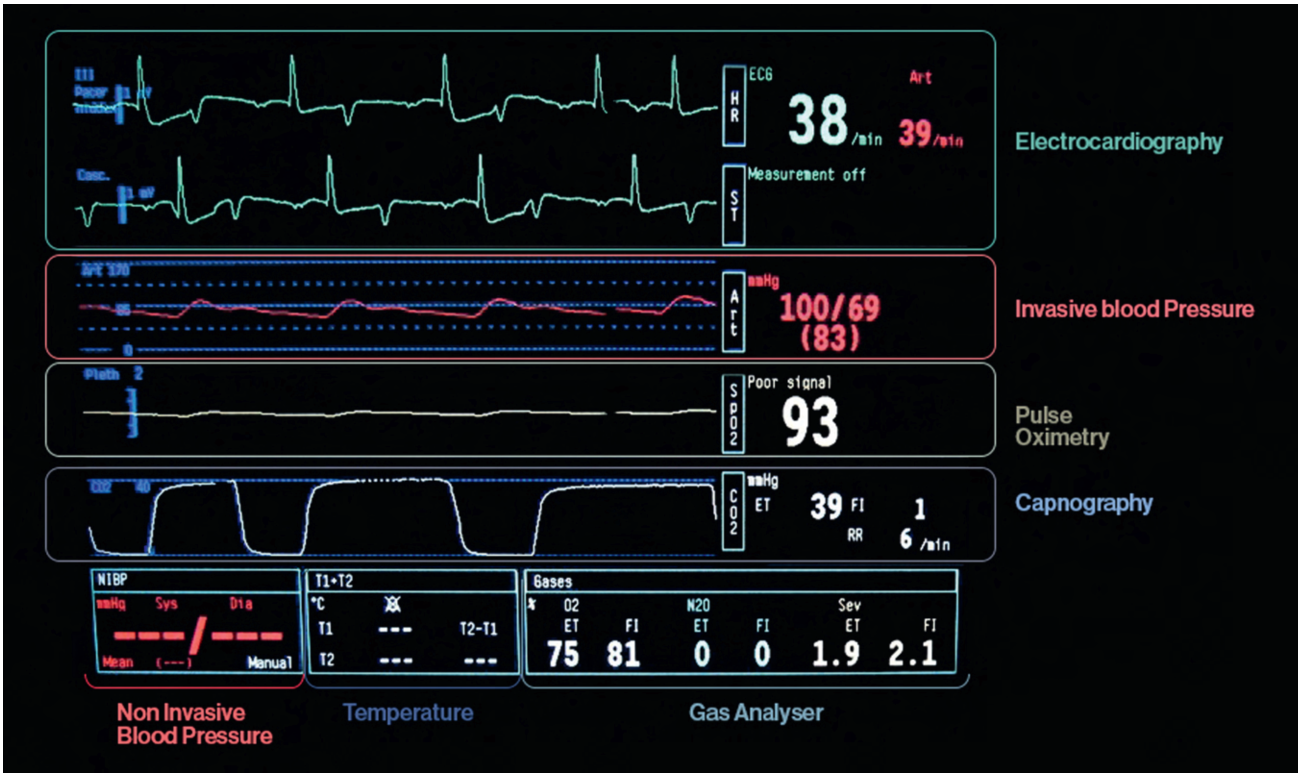


***Fig 7:** Anaesthetic monitor displaying electrocardiography, invasive blood pressure, pulse oximetry and capnography traces. Heart rates are shown for both the electrocardiography and arterial blood pressure traces. The gas analyser display shows oxygen, nitrogen oxide and sevoflurane analysis. Noninvasive blood pressure and dual site temperature monitoring is also possible, but not performed in this example. ET, end tidal; FI, fraction inspired; HR, heart rate; NIBP, noninvasive blood pressure; RR, respiratory rate; Sev, sevoflurane.*

research due to the invasive nature of the technique. Estimation of core temperature can be achieved by measuring rectal temperatures (Tomasic & Nann, 1999). Equine oesophageal temperature probes are commercially available (Vetronic Services Ltd.), but their accuracy is unknown.

Neuromuscular blockade

Neuromuscular blocking agents (NMBAs) confer muscle relaxation secondary to paralysis. It is not possible to monitor reflex activity (e.g. palpebral reflex) or muscle tone during neuromuscular blockade, making the assessment of plane of anaesthesia challenging. Sympathetic stimulation seen as an increase in HR or blood pressure could provide a nonspecific indication of nociception and/or inadequate anaesthetic plane. Ensuring adequate hypnosis and analgesia before and during the use of NMBA use is essential for welfare.

The use of nondepolarising agents (such as rocuronium or cis-atacurium) in horses has been described in ophthalmological surgery to achieve a central eye position and to facilitate orthopaedic procedures (Auer & Moens, 2011; Tutunaru et al., 2019). Monitoring the degree of neuromuscular block should always be performed to avoid residual neuromuscular block on recovery and to assist in decision making regarding the use of reversal agents (Bechara et al., 1999).

Assessing the corresponding muscular response to stimulation of a motor nerve provides information on the degree of neuromuscular blockade. This is because communication between the motor neuron and muscle end plate is blocked by NMBAs binding to motor end-plate acetylcholine receptors. The motor nerve selected depends on available access, but the superficial peroneal or radial nerve represent sensible choices (Martin-Flores, 2013; Mosing et al., 2010; Taylor & Clarke, 2007b; Tutunaru et al., 2019). The facial nerve may be a suboptimal choice due to the relative insensitivity of the corresponding muscles to NMBAs (Mosing et al., 2010). Positive and negative electrodes are connected directly over the nerve to be stimulated (Mosing et al., 2010). Correct placement should be verified prior to administration of NMBAs by observation of correct muscle activity in response to an electrical stimulus. Superficial peroneal nerve stimulation elicits pelvic limb digit extension, and radial nerve stimulation fore-limb digit extension.

There are a variety of nerve stimulation patterns that can be used (Martin-Flores, 2013), but a sequence of four supramaximal stimulating currents over 2 s is the most common and referred to as a 'train of four' (TOF). In the absence of paralysis, it elicits four sequential muscle twitches. Other stimulation patterns include a double-burst, single twitch and tetanic stimulation (Martin-Flores, 2013). Acceleromyography is the best described method for quantification of twitch activity and facilitates accurate assessment of the presence of residual neuromuscular blockade (Marly et al., 2013; Martin-Flores et al., 2008). An accelerometer is fixed to the hoof and the magnitude of the first twitch is compared to the fourth and a 'TOF ratio' calculated. Incomplete nondepolarising neuromuscular blockade exhibits a fade phenomenon, shown as decreasing twitch magnitudes in the TOF. This is observed during the onset and offset of the neuromuscular blockade. Complete neuromuscular blockade is characterised by no twitch activity, whilst the absence of neuromuscular blockade is characterised by a TOF ratio >0.9 (Martin-Flores, 2013; McGrath & Hunter, 2006). In horses, the ocular muscles are more sensitive to NMBA action than skeletal muscle, with the onset of a central globe occurring before a loss of TOF and persisting beyond the absence of skeletal muscle blockade (Auer & Moens, 2011).

Advanced methods of monitoring

Blood gas analysis

Patient-side, portable devices for ABG analysis facilitate rapid, direct, intermittent measurements of $PaCO_2$ and PaO_2 and calculated values for SaO_2. Acid–base balance, electrolytes, lactate, urea and creatinine may also be evaluated as part of the 'point-of-care' testing during anaesthesia (Langdon, 2018). Arterial sampling is an invasive procedure, and aseptic technique should be used. Dissolved oxygen is measured using a Clarke electrode by amperometry, as described by Langton and Hutton (2009). Samples drawn into plastic syringes should be analysed within 10 min to ensure accuracy (Picandet et al., 2007).

Continuous intra-arterial monitoring of patient oxygenation may become available for clinical use in equine patients. The technology is already available for humans and utilises miniature intra-arterial sensors (Ganter & Zollinger, 2003).

$PaCO_2$ measurement from arterial blood is performed using a Severinghaus electrode, utilising the acidic property of dissolved CO_2. Only CO_2 diffuses from the blood over a Teflon membrane into a bicarbonate buffer solution, which bathes an electrode that detects changes in pH (Langton & Hutton, 2009). The relationship between pH and $PaCO_2$ is linear between 1.2 and 12.0 kPa (9 – 90 mmHg) (Langton & Hutton, 2009), meaning ventilation should be considered when derangement in pH is present. However, mixed acid–base abnormalities may be present, so anion gap, bicarbonate and base excess should be carefully evaluated. Further detail on the use of acid–base analysis alongside ABG analysis is described by Alonso (2018).

Various patient-side analysers (the EPOC [Epocal Inc.], i-STAT [Abbot Laboratories] and StatPal II [SenDx Medical Inc.]) have been evaluated for the measurement of equine PaO_2, pH and P_aCO_2 in a clinical setting but they should not be used interchangeably (Bardell et al., 2016; Klein et al., 1999; Peiró et al., 2010). More recently, reference intervals for equine arterial blood gas, acid–base and electrolyte analysis have also been determined using the ABL 77 series (Radiometer Medical) (Hughes & Bardell, 2019).

Evaluating ABG and pH is recommended in cases where hypoxaemia and/or hypercapnia is suspected or likely to occur. However, it is not usually necessary in healthy, routine cases and is not usually performed in the field.

Cardiac output

Monitoring CO during equine anaesthesia is mainly reserved for research (Kutter et al., 2016). Despite this, CO measurement may enable guided fluid resuscitation and choice of cardiac support drugs during general anaesthesia (Corley et al., 2003) yet is rarely done in practice.

Pulmonary thermodilution requires catheterisation of a pulmonary artery via the jugular vein with a Swan-Ganz catheter. Cold saline is injected and exits the catheter proximal to a thermistor, which senses a change in temperature allowing calculation of CO (Corley et al., 2003). This technique is not suitable for clinical practice due to inaccuracies and the morbidity associated with pulmonary artery catheterisation (Corley & Marr, 2003).

The lithium dilution technique has been advocated as more suitable for clinical use (Corley & Marr, 2003). This technique requires central venous and peripheral arterial catheterisation, injection of lithium into the venous system and continuous arterial sampling at 4 ml/min during measurements (Corley et al., 2003; Shih, 2013). This generates a lithium concentration–time curve, from which the CO is calculated (Corley et al., 2003). Lithium dilution is expensive, produces intermittent measures of CO, and the concurrent use of drugs such as atacurium and xylazine interferes with measurements (Ambrisko & Moens, 2014; Shih, 2013). For experienced users, each measurement should require no more than 8 ml of blood to be sampled (Corley et al., 2003), but significant blood loss could occur with excessive measurements in very small patients such as neonates. Although considered an invasive technique, appropriate arterial and venous access may already be in place for IBP measurements and fluid therapy.

Pulse contour analysis represents a continuous, less invasive method for CO monitoring. It calculates CO from the arterial waveform produced by IBP measurements. Most devices require repeated calibration with lithium dilution or thermodilution techniques (Bendjelid, 2009). Conflicting evidence exists regarding the accuracy of devices in anaesthetised horses and foals (Hallowell & Corley, 2005; Schauvliege et al., 2009; Shih et al., 2009) with noncalibrated devices proving inaccurate (Kutter et al., 2016). Routine clinical use of pulse contour analysis cannot currently be recommended.

Measurement of lung volumes, gas pressures and flow

Spirometry is the objective, direct measurement of TV used to assess pulmonary function. Compliance is the change in lung volume per unit change in pressure and can also be calculated using spirometry. During mechanical ventilation, peak inspiratory pressure of the normal lung is between 20 and 35 cmH_20 (Mosing & Senior, 2018). Spirometry monitoring during equine anaesthesia most commonly requires a pitot tube within the breathing circuit and side stream sensing technology (Herholz, 2010; Moens et al., 2009). Breath-by-breath pressure–volume and flow-volume loops are generated for interpretation (Moens, 2010). The Tafonius (Vetronic Services Ltd) is an example of a large-animal anaesthetic machine with integrated spirometry measurement. Monitoring ventilation volumes can assist in early identification of anaesthetic machine and/or ventilator malfunction and obstructions within the airway (Moens, 2010). It can also allow informed decision making regarding mechanical ventilation, particularly where large changes in lung compliance are anticipated (e.g. severe abdominal distension) (Moens, 2013).

Volumetric capnography is a technique that combines measurement of $EtCO_2$ and ventilation volumes using capnography and flow sensors enabling a more comprehensive evaluation of expired CO_2 kinetics. Exhaled CO_2 depends on both airway perfusion and ventilation. Changes in these parameters influence the partial pressure of CO_2 from gases exhaled from various areas of the lungs (Blankman et al., 2016). This allows identification of the functional components of airway volume and measurement of dead space (lung areas that are ventilated but poorly perfused). Both flow and CO_2 sensors must be mainstream to facilitate simultaneous measurement (Mosing et al., 2018a; Schramel et al., 2014), and this may increase both resistance and dead space within the anaesthetic equipment. Volumetric capnography is not a common monitoring technique in equine anaesthesia but has been used to diagnose venous air embolism (Sacks & Mosing, 2016) and changes in airway volumes after recruitment manoeuvres in the anaesthetised horse (Ambrisko et al., 2014).

Emerging indirect, noninvasive methods to monitor ventilation that are not yet in routine use include electrical impedance tomography and ultrasonic plethysmography. Electrical impedance tomography correlates changes in electrical impedance across the thorax with changes in volumes across different lung regions (Mosing et al., 2017, 2019; Secombe et al., 2019). Ultrasonic plethysmography measures sound wave velocity across the thorax. Measurement bias and the requirement for sensors to be situated on the abdomen so they potentially obstruct surgical access make this method unlikely to replace spirometry in clinical practice (Russold et al., 2013).

Electroencephalography

Electroencephalography (EEG) is the recording of biological electrical activity from the cerebral cortex using surface electrodes placed on the head. There is a link between EEG activity and anaesthesia in humans and extensive patient data to characterise this (Barnard et al., 2007; Kearse et al., 1994; Kreuer & Wilhelm, 2006; Schneider et al., 2003). Monitoring EEG activity during equine anaesthesia is not common practice due to a lack of supporting evidence demonstrating its usefulness for interpreting plane of anaesthesia (Williams et al., 2016). Bispectral index (BIS) is a numerical scale based on analysis of human EEG data that reflects arousal level. BIS may be able to approximate consciousness in horses and represents a useful indicator of awakening when horses were anaesthetised with propofol infusions (Yamashita et al., 2009). However, during volatile anaesthesia, BIS has not been demonstrated as a reliable predictor for patient movement (Beldao et al., 2010; Haga & Dolvik, 2002). EEG monitoring and its calculated indices have shown more promise in evaluating nociception under anaesthesia in horses (Johnson et al., 1999, 2000; Murrell et al., 2003, 2005). Drewnowska et al. (2019) has comprehensively reviewed EEG monitoring during equine anaesthesia.

Concluding remarks

Monitoring the cardiorespiratory system and anaesthetic plane form the cornerstones of safe anaesthesia. Monitoring methodologies and associated technology range from simplistic to complex and trends in multiple parameters should be observed. It is recommended to utilise all basic monitoring techniques that require no equipment during general anaesthesia, such as ocular and mucous membrane assessment and pulse palpation, and document findings at least every five minutes. Capnography, pulse oximetry, electrocardiography and blood pressure monitoring (as shown in **Fig 7**) are to be considered as the most appropriate modalities alongside this basic monitoring as a minimum standard. During prolonged periods of general anaesthesia periods or for sick, high-risk patients, expired gas partial pressures, ABG analysis, temperature and invasive blood pressure assessment is also suggested. If NMBAs are used, a peripheral nerve stimulator is advised to assess depth of blockade in addition to the recommendations as above. These suggestions are similar to the guidelines produced by the American College of Veterinary Anaesthesia Equine Standards Committee (Hubbell & Werner, 2008; Martinez et al., 2008) with the additional consideration of NMBAs. If advanced monitoring such as EEG and spirometry is used, it is essential to understand the theory and limitations of such equipment.

Authors' declarations of interest

No conflicts of interest have been declared.

Ethical animal research

Not applicable.

Source of funding

None.

Authorship

C. Dagnall was responsible for the design and drafting of the manuscript, and drafting of figures. L. Khenissi and E. Love were responsible for commenting and editing the manuscript. All authors gave their final approval of the manuscript.

References

Ahn, K., Haruo, Y., Kiyoshi, T., Norio, Y., and Kweon, O. (1997) The relationship between arterial and end-tidal partial pressures of CO2 in halothane-anesthetized heavy breed horses with respect to operative positions and the modes of ventilation. *Korean Journal of Veterinary Research* **14**, 283. https://doi.org/10.1111/j.1751-0813.2009.00535.x.

Aida, H., Mizuno, Y., Hobo, S., Yoshida, K. and Fujinaga, T. (1994) Determination of the Minimum Alveolar Concentration (MAC) and Physical Response to Sevoflurane Inhalation in Horses. *Journal of Veterinary Medical Science* **56**, 1161-1165. https://doi.org/10.1292/jvms.56.1161.

Alonso, G. (2018) Blood gases. In: *Interpretation of Equine Laboratory Diagnostics*. Pusterla, N. and Higgins, J. (Eds). John Wiley & Sons Inc, Hoboken, NJ. pp. 57-65.

Ambrisko, T.D., Lammer, V., Schramel, J.P. and Moens, Y.P.S. (2014) In vitro and in vivo evaluation of a new large animal spirometry device using mainstream CO2 flow sensors. *Equine Veterinary Journal* **46**, 507-511. https://doi.org/10.1111/evj.12140.

Ambrisko, T.D. and Moens, Y. (2014) Voltage changes in the lithium dilution cardiac output sensor after exposure to blood from horses given xylazine. *British Journal of Anaesthesia* **112**, 367-369. https://doi.org/10.1093/bja/aet298.

Anaesthesia Gas Monitoring: Evolution of a de facto Standard of Care (2009) ProMed Strategies for Masimo Phase, In: Sweden. Available online: https://www.masimo.co.uk/siteassets/uk/documents/pdf/


PARTNERS MAKE THE DIFFERENCE
LASTING PARTNERSHIPS PRODUCE
ENDURING FRIENDSHIPS
AAEP's Educational and Media Partners create opportunities for the AAEP and its members to help bridge the difference between the ordinary and the extraordinary. Together with their support, we can continue to advance the health and welfare of our patients and profession.
Educational Partners
AMERICAN REGENT™ ANIMAL HEALTH
Boehringer Ingelheim
CareCredit®
Making care possible...today.
Cargill®
contura vet
Dechra
Veterinary Products
IDEXX
MERCK
Animal Health
PLATINUM PERFORMANCE
Good Nutrition is Good Medicine®
PURINA
zoetis
Media Partners
EquiManagement
Business Solutions for Equine Practitioners
EQUUS
the HORSE
YOUR GUIDE TO EQUINE HEALTH CARE
AAEP
American Association of Equine Practitioners
aaep.org

clinical-evidence/whitepapers/lab8175a_whitepapers_anaesthesia_gas_monitoring_british.pdf [Accessed 22/01/2021].

Auckburally, A. and Nyman, G. (2017) Review of hypoxaemia in anaesthetized horses: predisposing factors, consequences and management. *Veterinary Anaesthesia and Analgesia* **44**, 397-408. https://doi.org/10.1016/j.vaa.2016.06.001.

Auer, U. and Moens, Y.P. (2011) Neuromuscular blockade with rocuronium bromide for ophthalmic surgery in horses. *Veterinary Ophthalmology* **14**, 244-247. https://doi.org/10.1111/j.1463-5224.2010.00870.x.

Bardell, D., Mosing, M. and Cripps, P.J. (2020) Restoration of arterial oxygen tension in horses recovering from general anaesthesia. *Equine Veterinary Journal* **52**, 187-193. https://doi.org/10.1111/evj.13142.

Bardell, D., West, E. and Senior, J.M. (2016) Evaluation of a new handheld point-of-care blood gas analyser using 100 equine blood samples. *Veterinary Anaesthesia and Analgesia* **44**, 77-85. https://doi.org/10.1111/vaa.12392.

Barnard, J.P., Bennett, C., Voss, L.J. and Sleigh, J.W. (2007) Can anaesthetists be taught to interpret the effects of general anaesthesia on the electroencephalogram? Comparison of performance with the BIS and spectral entropy. *British Journal of Anaesthesia* **99**, 532-537. https://doi.org/10.1093/bja/aem198.

Barr, E.D., Clegg, P.D., Senior, J.M. and Singer, E.R. (2005) Destructive lesions of the proximal sesamoid bones as a complication of dorsal metatarsal artery catheterization in three horses. *Veterinary Surgery* **34**, 159-166. https://doi.org/10.1111/j.1532-950X.2005.00026.x.

Bechara, J.N., Fantoni, D.T., de Barros, P.S. Migliati, E.R., Ferreira, M.A. and da Silva, L.C.L.C. (1999) The TOF-guard neuromuscular transmission monitor and its use in horses. *Ciência Rural* **29**, 57-62. https://doi.org/10.1590/S0103-84781999000100011.

Bednarski, R.M. and Muir, W. (2009) Capnography in veterinary medicine. In: *Capnographry*. 2nd edn. Eds: J. Gravenstein, M. Jaffe, N. Gravenstein and D. Paulus. Cambridge University Press, Cambridge. pp 272-280.

Beldao, E., Blissitt, K.J., Duncan, J.C., Laredo, F.G., de Montes, M.E.G. and Clutton, R.E. (2010) The bispectral index during recovery from halothane and sevoflurane anaesthesia in horses. *Veterinary Anaesthesia and Analgesia* **37**, 25-34. https://doi.org/10.1111/j.1467-2995.2009.00507.x.

Bendjelid, K. (2009) When to recalibrate the PiCCOTM? From a physiological point of view, the answer is simple. *Acta Anaesthesiologica Scandinavica* **53**, 689-690. https://doi.org/10.1111/j.1399-6576.2009.01919.x.

Benson, G.J., Manohar, M., Kneller, S.K., Thurmon, J.C. and Steffey, E.P. (1982) Radiographic characterization of diaphragmatic excursion in halothane anesthetized ponies: Spontaneous and controlled ventilation systems. *American Journal of Veterinary Research* **43**, 617-662.

Bidwell, L.A., Bramlage, L.R. and Rood, W.A. (2007) Equine perioperative fatalities associated with general anaesthesia at a private practice – a retrospective case series. *Veterinary Anaesthesia and Analgesia* **34**, 23-30.

Blankman, P., Shono, A., Hermans, B.J.M., Wesselius, T., Hasan, D. and Gommers, D. (2016) Detection of optimal PEEP for equal distribution of tidal volume by volumetric capnography and electrical impedance tomography during decreasing levels of PEEP in post cardiac-surgery patients. *British Journal of Anaesthesia* **116**, 862-869. https://doi.org/10.1093/bja/aew116.

Branson, K.R. (1997) A clinical evaluation of an oscillometric blood pressure monitor on anesthetized horses. *Journal of Equine Veterinary Science* **17**, 537-540. https://doi.org/10.1016/S0737-0806(97)80226-2.

Brightman, A.H., Manning, J.P., Benson, G.J. and Musselman, E.E. (1983) Decreased tear production associated with general anesthesia in the horse. *Journal of the American Veterinary Medical Association* **182**, 243-244.

Brosnan, R.J. (2013) Inhaled anesthetics in horses. *The Veterinary Clinics of North America. Equine Practice* **29**, 69-87. https://doi.org/10.1016/j.cveq.2012.11.006.

Brosnan, R.J., Steffey, E.P., LeCouteur, R.A., Imai, A., Farver, T.B. and Kortz, G.D. (2003) Effects of ventilation and isoflurane end-tidal concentration on intracranial and cerebral perfusion pressures in horses. *American Journal of Veterinary Research* **64**, 21-25. https://doi.org/10.2460/ajvr.2003.64.21.

Cambier, C., Passio, N.D., Clerbaux, T., Amory, H., Marville, V., Detry, B. et al. (2005) Blood–oxygen binding in healthy Standardbred horses. *The Veterinary Journal* **169**, 251-256. https://doi.org/10.1016/j.tvjl.2004.01.025.

Chaffin, M.K., Matthews, N.S., Cohen, N.D. and Carter, G.K. (1996) Evaluation of pulse oximetry in anaesthetised foals using multiple combinations of transducer type and transducer attachment site. *Equine Veterinary Journal* **28**, 437-445. https://doi.org/10.1111/j.2042-3306.1996.tb01615.x.

Chan, E.D., Chan, M.M. and Chan, M.M. (2013) Pulse oximetry: Understanding its basic principles facilitates appreciation of its limitations. *Respiratory Medicine* **107**, 789-799. https://doi.org/10.1016/j.rmed.2013.02.004.

Clerbaux, T., Serteyn, D., Willems, E. and Brasseur, L. (1986) Determination of the standard oxyhemoglobin dissociation curve in horses. Effects of temperature, pH and diphosphoglycerate. *Canadian Journal of Veterinary Research* **50**, 188-192.

Corley, K.T.T., Donaldson, L.L., Durando, M.M. and Birks, E.K. (2003) Cardiac output technologies with special reference to the horse. *Journal of Veterinary Internal Medicine* **17**, 262-272. https://doi.org/10.1111/j.1939-1676.2003.tb02447.x.

Corley, K.T.T. and Marr, C.M. (2003) Cardiac monitoring in the ICU patient. *Clinical Techniques in Equine Practice* **2**, 145-155. https://doi.org/10.1016/S1534-7516(03)00003-9.

Cribb, P.H. (1988) Capnographic monitoring during anesthesia with controlled ventilation in the Horse. *Veterinary Surgery* **17**, 48-52. https://doi.org/10.1111/j.1532-950x.1988.tb00274.x.

Day, T.K., Gaynor, J.S., Muir, W.W. III, Bednarski, R.M. and Mason, D.E. (1995) Blood gas values during intermittent positive pressure ventilation and spontaneous ventilation in 160 Anesthetized Horses Positioned in Lateral or Dorsal Recumbency. *Veterinary Surgery* **24**, 266-276. https://doi.org/10.1111/j.1532-950x.1995.tb01330.x.

Drewnowska, O., Lisowska, B. and Turek, B. (2019) What do we know about the use of EEG monitoring during equine anesthesia: A review. *Appl Sci* **9**, 3678. https://doi.org/10.3390/app9183678.

Dugdale, A.H. and Taylor, P.M. (2016) Equine anaesthesia-associated mortality: where are we now? *Veterinary Anaesthesia and Analgesia* **43**, 242-255.

Dujardin, C.L., Gootjes, P. and Moens, Y. (2005) Isoflurane measurement error using short wavelength infrared techniques in horses: influence of fresh gas flow and pre-anaesthetic food deprivation. *Veterinary Anaesthesia and Analgesia* **32**, 101-106. https://doi.org/10.1111/j.1467-2995.2004.00185.x.

Duke, T., Filzek, U., Read, M.R., Read, E.K. and Ferguson, J.G. (2006) Clinical observations surrounding an increased incidence of postanesthetic myopathy in halothane-anesthetized horses. *Veterinary Anaesthesia and Analgesia* **33**, 122-127. https://doi.org/10.1111/j.1467-2995.2005.00189.x.

Dunlop, C.S., Hodgson, D.S. and Grandy, J.L. (1989) The MAC of isoflurane in foals. *Veterinary Surgery* **18**, 247-254.

Edner, A., Nyman, G. and Essén-Gustavsson, B. (2005) The effects of spontaneous and mechanical ventilation on central cardiovascular function and peripheral perfusion during isoflurane anaesthesia in horses. *Veterinary Anaesthesia and Analgesia* **32**, 136-146. https://doi.org/10.1111/j.1467-2995.2005.00190.x.

Eisele, J.H., Eger, E.I. and Muallem, M. (1967) Narcotic properties of carbon dioxide in the dog. *Anesthesiology* **28**, 856-865. https://doi.org/10.1097/00000542-196709000-00019.

Franci, P., Leece, E.A. and Brearly, J.C. (2006) Post anaesthetic myopathy/neuropathy in horses undergoing magnetic resonance imaging compared to horses undergoing surgery. *Equine Veterinary Journal* **38**, 497-501. https://doi.org/10.2746/042516406x156505.

Frank, S.M., Fleisher, L.A., Breslow, M.J., Higgins, M.S., Olson, K.F., Kelly, S. and et al. (1997) Perioperative maintenance of normothermia reduces the incidence of morbid cardiac events: A randomized clinical trial. *JAMA* **277**, 1127-1134.

Ganter, M. and Zollinger, A. (2003) Continuous intravascular blood gas monitoring: development, current techniques, and clinical use of a commercial device. *British Journal of Anaesthesia* **91**, 397-407. https://doi.org/10.1093/bja/aeg176.

Garg, R. and Gupta, R.C. (2013) Analysis of oxygen, anaesthesia agent and flows in anaesthesia machine. *Indian Journal of Anaesthesia* **57**, 481-488. https://doi.org/10.4103/0019-5049.120144.

Gasthuys, F., Martens, A., Goossens, L. and De Moor, A. (1996) A quantitative study of the diuretic effects of romifidine in the horse. *Journal of Veterinary Anaesthesia* **23**, 6-10. https://doi.org/10.1111/j.1467-2995.1996.tb00274.

Geiser, D.R. and Rohrbach, B.W. (1992) Use of end-tidal CO2 tension to predict arterial CO2 values in isoflurane-anesthetized equine neonates. *American Journal of Veterinary Research* **53**, 1617-1621.

Gent, T.C., Schwarz, A., Hatz, L.A., Gozalo-Marcilla, M., Schauvliege, S., Gasthuys, F.F. and et al. (2015) Evaluation of accuracy of invasive and non-invasive blood pressure monitoring in relation to carotid artery pressure in anaesthetised ponies. *Pferdeheilkunde* **31**, 33-38.

Giguère, S., Knowles, H.A., Valverde, A., Bucki, E. and Young, L. (2005) Accuracy of indirect measurement of blood pressure in neonatal foals. *Journal of Veterinary Internal Medicine* **19**, 571-576. https://doi.org/10.1111/j.1939-1676.2005.tb02729.x.

Giguère, S., Sanchez, L.C. and Shih, A. (2014) Accuracy of calculated arterial saturation in oxygen in neonatal foals and effects of monitor, sensor, site of sensor placement, and degree of hypoxemia on the accuracy of pulse oximetry. *Journal of Veterinary Emergency and Critical Care* **24**, 529-535. https://doi.org/10.1111/vec.12231.

Gozalo-Marcilla, M., Redondo, J.I., Johnston, M., Taylor, P. and Bettschart-Wolfensberger, R. (2020) CEPEF4: update and plan. *Veterinary Anaesthesia and Analgesia* **47**(**5**), 724-772. https://doi.org/10.1016/j.vaa.2020.08.004.

Grandy, J.L., Steffey, E.P., Hodgson, D.S. and Woliner, M.J. (1987) Arterial hypotension and the development of postanesthetic myopathy in halothane-anesthetized horses. *American Journal of Veterinary Research* **48**, 192-197.

Guedel, A.E. (1927) Stages of Anesthesia and a re-classification of the signs of anesthesia. *Current Researches in Anesthesia & Analgesia* **6**(**4**), 157-162.

Haga, H.A. and Dolvik, N.I. (2002) Evaluation of the bispectral index as an indicator of degree of central nervous system depression in isoflurane-anesthetized horses. *American Journal of Veterinary Research* **63**, 438-442. https://doi.org/10.2460/ajvr.2002.63.438.

Hall, L.W., Gillespie, J.R. and Tyler, W.S. (1968) Alveolar-arterial oxygen tension differences in anaesthetised horses. *British Journal of Anaesthesia* **40**, 560-568. https://doi.org/10.1093/bja/40.8.560.

Hallowell, G.D. and Corley, K.T. (2005) Use of lithium dilution and pulse contour analysis cardiac output determination in anaesthetized horses: a clinical evaluation. *Veterinary Anaesthesia and Analgesia* **32**, 201-211. https://doi.org/10.1111/j.1467-2995.2005.00249.x.

Haskins (2015) Monitoring anaesthetised patients. In: *Veterinary Anaesthesia and Analgesia*, Eds: K.A. Grimm, L.A. Lamont, W.J. Tranquilli, S.A. Greene and S. Robertson https://doi.org/10.1002/9781119421375.ch4

Hatz, L., Hartnack, S., Kümmerle, J., Hässig, M. and Bettschart-Wolfensberger, R. (2015) A study of measurement of noninvasive blood pressure with the oscillometric device, Sentinel, in isoflurane-anaesthetized horses. *Veterinary Anaesthesia and Analgesia* **42**, 369-376. https://doi.org/10.1111/vaa.12213.

Heliczer, N., Lorello, O., Casoni, D. and de Solis, C.N. (2016) Accuracy and precision of noninvasive blood pressure in normo-, hyper-, and hypotensive standing and anesthetized adult horses. *Journal of Veterinary Internal Medicine* **30**, 866-872. https://doi.org/10.1111/jvim.13928.

Herholz, C. (2010) Clinical application of continuous spirometry during equine anaesthesia and in spontaneous breathing, awake horses. *Equine Veterinary Education* **22**, 361-363. https://doi.org/10.1111/j.2042-3292.2010.00089.x.

Hubbell, J.A. (2010) Review of support of ventilation in the anaesthetized horse. In: Proceedings of the 56th Annual Convention of the American Association of Equine Practitioners. Baltimore, Maryland, USA. 56, 33-37

Hubbell, J.A.E. and Muir, W.W. (2009) Chapter 8 - Monitoring Anaesthesia. *Equine Anaesthesia*, 2nd edn, Saunders Elsevier, Missouri, MO. pp 149-170.

Hubbell, J.A.E., Saville, W.J.A. and Bednarski, R.M. (2010) The use of sedatives, analgesic and anaesthetic drugs in the horse: An electronic survey of members of the American Association of Equine Practitioners (AAEP). *Equine Veterinary Journal* **42**, 487-493. https://doi.org/10.1111/j.2042-3306.2010.00104.x.

Hubbell, J.A. and Werner, H.W. (2008) A review of the American College of Veterinary Anesthesiologists guidelines for anesthesia of horses. In: Proceedings of the 54 th Annual Convention of the American Association of Equine Practitioners. San Diego, California, USA. 54, 48-53

Hughes, J. and Bardell, D. (2019) Determination of reference intervals for equine arterial blood-gas, acid-base and electrolyte analysis. *Veterinary Anaesthesia and Analgesia* **46**, 765-771.

Jago, R.C., Corletto, F. and Wright, I.M. (2015) Peri-anaesthetic complications in an equine referral hospital: Risk factors for post anaesthetic colic. *Equine Veterinary Journal* **47**, 635-640.

Johnson, C.B., Bloomfield, M. and Taylor, P.M. (1999) Effects of ketamine on the equine electroencephalogram during anesthesia with halothane in oxygen. *Veterinary Surgery* **28**, 380-385. https://doi.org/10.1111/j.1532-950x.1999.00380.x.

Johnson, C., Bloomfield, M. and Taylor, P. (2000) Effects of thiopentone on the equine electroencephalogram during anaesthesia with halothane in oxygen. *Veterinary Anaesthesia and Analgesia* **27**, 82-88. https://doi.org/10.1046/j.1467-2995.2000.00022.x.

Johnston, G., Eastment, J., Wood, J. and Taylor, P. (2002) The confidential enquiry into perioperative equine fatalities (CEPEF): mortality results of Phases 1 and 2. *Veterinary Anaesthesia and Analgesia* **29**, 159-170. https://doi.org/10.1111/vaa.12372.

Kearse, L.A., Manberg, P., Chamoun, N., deBros, F. and Zaslavsky, A. (1994) Bispectral analysis of the electroencephalogram correlates with patient movement to skin incision during propofol/nitrous oxide anesthesia. *Anesthesiology* **81**, 1365-1370. https://doi.org/10.1097/00000542-199412000-00010.

Kelleher, J.F. (1989) Pulse oximetry. *Journal of Clinical Monitoring* **5**, 37-62. https://doi.org/10.1007/BF01618369.

Khanna, A.K., McDonell, W.N., Dyson, D.H. and Taylor, P.M. (1995) Cardiopulmonary effects of hypercapnia during controlled intermittent positive pressure ventilation in the horse. *Canadian Journal of Veterinary Research* **59**, 213-221.

Klein, L.V., Soma, L.R. and Nann, L.E. (1999) Accuracy and precision of the portable StatPal II and the laboratory-based NOVA Stat Profile 1 for measurement of pH, Pco2, and Po2 in equine blood. *Veterinary Surgery* **28**, 67-76. https://doi.org/10.1053/jvet.1999.0067.

Koenig, J., McDonell, W. and Valverde, A. (2003) Accuracy of pulse oximetry and capnography in healthy and compromised horses during spontaneous and controlled ventilation. *Canadian Journal of Veterinary Research* **67**, 169-174.

Koterba, A.M., Kosch, P.C., Beech, J. and Whitlock, T. (1985) Breathing strategy of the adult horse (Equus caballus) at rest. *Journal of Applied Physiology* **64**(**1**), 337-346.

Kotsovolis, G. and Komninos, G. (2009) Awareness during anesthesia: how sure can we be that the patient is sleeping indeed? *Hippokratia* **13**, 83-89.

Kreuer, S. and Wilhelm, W. (2006) The Narcotrend monitor. *Best Practice & Research Clinical Anaesthesiology* **20**, 111-119. https://doi.org/10.1016/j.bpa.2005.08.010.

Kutter, A.P., Bettschart-Wolfensberger, R., Schwarzwald, C.C., Portier, K.G. and Ringer, S.K. (2016) Evaluation of the non-calibrated pulse contour cardiac output monitor FloTrac/Vigileo against thermodilution in standing horses. *Veterinary Anaesthesia and Analgesia* **43**, 153-162. https://doi.org/10.1111/vaa.12281.

Langdon, F.C. (2018) Point-of-Care Testing. In: *Interpretation of Equine Laboratory Diagnostics*. Eds: N. Pusterla and J. Higgins. John Whiley

& Sons Inc, Hoboken, NJ. pp 23-26. https://doi.org/10.1002/9781118922798.ch3

Langton, J.A. and Hutton, A. (2009) Respiratory gas analysis. *Continuing Education in Anaesthesia Critical Care & Pain* **9**, 19-23. https://doi.org/10.1093/bjaceaccp/mkn048.

Latshaw, H., Fessler, J.F., Whistler, S.J. and Geddes, L.A. (1979) Indirect measurement of mean blood pressure in the normotensive and hypotensive horse. *Equine Veterinary Journal* **11**, 191-194. https://doi.org/10.1111/j.2042-3306.1979.tb01340.x.

Le Chevallier, D. and Van Oostrom, H. (2020) Falsely low arterial blood pressure due to pressure transducer damage in three horses. *Veterinary Record Case Reports* **8**, e000985. https://doi.org/10.1136/vetreccr-2019-000985.

Leonardi, F., Costa, G.L., Dubau, M., Sabbioni, A., Simonazzi, B. and Angelone, M. (2020) Effects of intravenous romifidine, detomidine, detomidine combined with butorphanol, and xylazine on tear production in horses. *Equine Veterinary Education* **32**, 53-57.

Marly, C., Gent, T. and Mosing, M. (2013) Practical application of acceleromyography to monitor neuromuscular block in a horse. *Veterinary Anaesthesia and Analgesia* **40**, 554-556. https://doi.org/10.1111/vaa.12049.

Martinez, E.A., Carroll, G.L. and Hartsfield, S.M. (1999) Evaluation of the Nonin 8600V veterinary pulse oximeter in anesthetized horses. *Journal of Veterinary Emergency and Critical Care* **9**, 13-17. https://doi.org/10.1111/j.1476-4431.1999.tb00134.x.

Martinez, E.A., Wagner, A.E., Driessen, B. and Trim, C. (2008) American College of Veterinary Anesthesiologists guidelines for anesthesia in horses. Available online: https://acvaa.org/wp-content/uploads/2019/05/Guidelines-for-Anesthesia-in-Horses.pdf [Accessed 30/01/2021].

Martin-Flores, M. (2013) Neuromuscular blocking agents and monitoring in the equine patient. *The Veterinary Clinics of North America. Equine Practice* **29**, 131-154. https://doi.org/10.1016/j.cveq.2012.11.010.

Martin-Flores, M., Campoy, L., Ludders, J.W., Erb, H.N. and Gleed, R.D. (2008) Comparison between acceleromyography and visual assessment of train-of-four for monitoring neuromuscular blockade in horses undergoing surgery. *Veterinary Anaesthesia and Analgesia* **35**, 220-227. https://doi.org/10.1111/j.1467-2995.2007.00380.x.

Matthews, N.S., Hartsfield, S.M., Sanders, E.A., Light, G.S. and Slater, M.S. (1994) Evaluation of pulse oximetry in horses surgically treated for colic. *Equine Veterinary Journal* **26**, 114-116. https://doi.org/10.1111/j.2042-3306.1994.tb04347.x.

Mayerhofer, I., Scherzer, S., Gabler, C. and Hoven, R. (2005) Hypothermia in horses induced by general anaesthesia and limiting measures. *Equine Veterinary Education* **17**, 53-56. https://doi.org/10.1111/j.2042-3292.2005.tb00336.x.

McConachie, E.L., Giguère, S., Rapoport, G. and Barton, M.H. (2016) Heart rate variability in horses with acute gastrointestinal disease requiring exploratory laparotomy. *Journal of Veterinary Emergency and Critical Care* **26**, 269-280. https://doi.org/10.1111/vec.12362.

McDonell, W.N. and Kerr, K.L. (2015) Physiology, pathophysiology and anaesthetic management of patients with respiratory disease. In: *Veterinary Anaesthesia and Analgesia*. Eds: K.A. Grimm, L.A. Lamont, W.J. Tranquilli, S.A. Greene and S. Robertson. https://doi.org/10.1002/9781119421375.ch27

McGrath, C.D. and Hunter, J.M. (2006) Monitoring of neuromuscular block. *Continuing Education in Anaesthesia Critical Care & Pain* **6**, 7-12. https://doi.org/10.1093/bjaceaccp/mki067.

Medd, W.E., French, E.B. and Wyllie, V.M. (1959) Cyanosis as a guide to arterial oxygen desaturation. *Thorax* **14**, 247-250. https://doi.org/10.1136/thx.14.3.247.

Merkel, G. and Eger, E.I. (1963) A comparative study of halothane and halopropane anesthesia including method for determining equipotency. *Survey of Anesthesiology* **18**, 574-586. https://doi.org/10.1097/00132586-197412000-00034.

Meyer, R.E. and Short, C.E. (1985) Arterial to end-tidal CO2 tension and alveolar dead space in halothane- or isoflurane-anesthetized ponies. *American Journal of Veterinary Research* **46**, 597-599. PMID: 3922264.

Mitchell, K.J. (2019) Equine electrocardiography. *The Veterinary Clinics of North America. Equine Practice* **35**, 65-83. https://doi.org/10.1016/j.cveq.2018.12.007.

Moens, Y.P. (1989) Arterial-alveolar carbon dioxide tension difference and alveolar dead space in halothane anaesthetised horses. *Equine Veterinary Journal* **21**, 282-284. https://doi.org/10.1111/j.2042-3306.1989.tb02168.x.

Moens, Y.P. (2010) Clinical application of continuous spirometry with a pitot-based flow meter during equine anaesthesia. *Equine Veterinary Education* **22**, 354-360. https://doi.org/10.1111/j.2042-3292.2010.00066.x.

Moens, Y.P. (2013) Mechanical ventilation and respiratory mechanics during equine anesthesia. *The Veterinary Clinics of North America. Equine Practice* **29**, 51-67. https://doi.org/10.1016/j.cveq.2012.12.002.

Moens, Y.P., Gootjes, P. and Lagerweij, E. (1991) The influence of methane on the infrared measurement of halothane in the horse. *Veterinary Anaesthesia and Analgesia* **18**, 4-7. https://doi.org/10.1111/j.1467-2995.1991.tb00004.x.

Moens, Y.P., Gootjes, P., Ionita, J., Heinonen, E. and Schatzmann, U. (2009) In vitro validation of a Pitot-based flow meter for the measurement of respiratory volume and flow in large animal anaesthesia. *Veterinary Anaesthesia and Analgesia* **36**, 209-219. https://doi.org/10.1111/j.1467-2995.2009.00449.x.

Mosing, M., Auer, U., Bardell, D., Jones, R.S. and Hunter, J.M. (2010) Reversal of profound rocuronium block monitored in three muscle groups with sugammadex in ponies. *British Journal of Anaesthesia* **105**, 480-486. https://doi.org/10.1093/bja/aeq172.

Mosing, M., Auer, U., MacFarlane, P., Bardell, D., Schramel, J.P., Böhm, S.H. et al. (2018a) Regional ventilation distribution and dead space in anaesthetized horses treated with and without continuous positive airway pressure: novel insights by electrical impedance tomography and volumetric capnography. *Veterinary Anaesthesia and Analgesia* **45**, 31-40. https://doi.org/10.1016/j.vaa.2017.06.004.

Mosing, M., Böhm, S.H., Rasis, A., Hoosgood, G., Auer, U., Tusman, G. et al. (2018b) Physiologic factors influencing the arterial-to-end-tidal CO2 difference and the alveolar dead space fraction in spontaneously breathing anesthetised horses. *Frontiers in Veterinary Science* **5**, 58. https://doi.org/10.3389/fvets.2018.00058.

Mosing, M., Marly-Voquer, C., MacFarlane, P., Bardell, D., Böhm, S.H., Bettschart-Wolfensberger, R. and et al. (2017) Regional distribution of ventilation in horses in dorsal recumbency during spontaneous and mechanical ventilation assessed by electrical impedance tomography: a case series. *Veterinary Anaesthesia and Analgesia* **44**, 127-132. https://doi.org/10.1111/vaa.12405.

Mosing, M. and Senior, J.M. (2018) Maintenance of equine anaesthesia over the last 50 years: Controlled inhalation of volatile anaesthetics and pulmonary ventilation. *Equine Veterinary Journal* **50**, 282-291. https://doi.org/10.1111/evj.12793.

Mosing, M., Waldmann, A.D., Raisis, A., Böhm, S.H., Drynan, E. and Wilson, K. (2019) Monitoring of tidal ventilation by electrical impedance tomography in anaesthetised horses. *Equine Veterinary Journal* **51**, 222-226. https://doi.org/10.1111/evj.12998.

Moxham, I.M. (2003) Physics of invasive blood pressure monitoring. *Southern African Journal of Anaesthesia and Analgesia* **9**, 33-38. https://doi.org/10.1080/22201173.2003.10872990.

Muir, W.W., Wade, A. and Grospitch, B. (1983) Automatic noninvasive sphygomanometry in horses. *Journal of the American Veterinary Medical Association* **182**, 1230-1233.

Murrell, J.C., Johnson, C.B., White, K.L., Taylor, P.M., Haberham, Z.L. and Waterman-Pearson, A.E. (2003) Changes in the EEG during castration in horses and ponies anaesthetized with halothane. *Veterinary Anaesthesia and Analgesia* **30**, 138-146. https://doi.org/10.1046/j.1467-2995.2003.00138.x.

Murrell, J.C., White, K.L., Johnson, C.B., Taylor, P.M., Doherty, T.J. and Waterman-Pearson, A.E. (2005) Investigation of the EEG effects of intravenous lidocaine during halothane anaesthesia in ponies. *Veterinary Anaesthesia and Analgesia* **32**, 212-221. https://doi.org/10.1111/j.1467-2995.2005.00201.x.

Neto, F.J.T., Luna, S.P.L., Massone, F., Thomassian, A., Vargas, J.L.R., Junior, J.R.S. et al. (2000) The effect of changing the mode of ventilation on the arterial-to-end-tidal CO2 difference and physiological dead space in laterally and dorsally recumbent horses during halothane anesthesia. *Veterinary Surgery* **29**, 200-205. https://doi.org/10.1111/j.1532-950x.2000.00200.x.

Nicolaisen, A.-S.-K., Nygaard, A.B., Christophersen, M.T., Jensen, D.B. and Lindegaard, C. (2022) Effect of head and tail rope-assisted recovery of horses after elective and emergency surgery under general anaesthesia. *Equine Veterinary Education*. **34**, 126-133. https://doi.org/10.1111/eve.13397.

Nout, Y.S., Corley, K.T.T., Donaldson, L.L. and Furr, M.O. (2002) Indirect oscillometric and direct blood pressure measurements in anesthetized and conscious neonatal foals. *Journal of Veterinary Emergency and Critical Care* **12**, 75-80. https://doi.org/10.1046/j.1435-6935.2002.00027.x.

Nuñez, E., Steffey, E.P., Ocampo, L., Rodriguez, A. and Garcia, A.A. (2004) Effects of alpha2-adrenergic receptor agonists on urine production in horses deprived of food and water. *American Journal of Veterinary Research* **65**, 1342-1346. https://doi.org/10.2460/ajvr.2004.65.1342.

Nyman, G., Grubb, T.L., Heinonen, E., Frendin, J., Edner, A., Malavasi, L.M. et al. (2012) Pulsed delivery of inhaled nitric oxide counteracts hypoxaemia during 2.5 hours of inhalation anaesthesia in dorsally recumbent horses. *Veterinary Anaesthesia and Analgesia* **39**, 480-487. https://doi.org/10.1111/j.1467-2995.2012.00740.x.

Nyman, G. and Hedenstierna, G. (1989) Ventilation-perfusion relationships in the anaesthetised horse. *Equine Veterinary Journal* **21**, 274-281. https://doi.org/10.1111/j.2042-3306.1989.tb02167.x.

O'Rourke, M.F. and Yaginuma, T. (1984) Wave Reflections and the Arterial Pulse. *Archives of Internal Medicine* **144**, 366-371.

Otteni, J.C. (1993) FiO2 monitor still has important role. APSF, **8**, Available online: https://www.apsf.org/article/fio2-monitor-still-has-important-role/ [Accessed 21/01/2021]

Parviainen, A.K. and Trim, C.M. (2000) Complications associated with anaesthesia for ocular surgery: a retrospective study 1989–1996. *Equine Veterinary Journal* **32**, 555-559. https://doi.org/10.2746/042516400777584659.

Pascoe, P.J., McDonell, W.N., Trim, C.M. and Gorder, J.V. (1983) Mortality rates and associated factors in equine colic operations - a retrospective study of 341 operations. *Canadian Veterinary Journal* **24**, 76-85.

Peek, M.L. (1993) A case of post-anaesthetic myopathy. *Equine Veterinary Education* **5**, 183-186. https://doi.org/10.1111/j.2042-3292.1993.tb01039.x.

Peiró, J.R., Borges, A.S., Gonçalves, R.C. and Mendes, L.C.N. (2010) Evaluation of a portable clinical analyzer for the determination of blood gas partial pressures, electrolyte concentrations, and hematocrit in venous blood samples collected from cattle, horses, and sheep. *American Journal of Veterinary Research* **71**, 515-521. https://doi.org/10.2460/ajvr.71.5.515.

Picandet, V., Jeanneret, S. and Lavoie, J. (2007) Effects of syringe type and storage temperature on results of blood gas analysis in arterial blood of horses. *Journal of Veterinary Internal Medicine* **21**, 476-481.

Portier, K., Crouzier, D., Guichardant, M., Prost, M., Debouzy, J., Kirschvink, N. et al. (2009) Effects of high and low inspired fractions of oxygen on horse erythrocyte membrane properties, blood viscosity and muscle oxygenation during anaesthesia. *Veterinary Anaesthesia and Analgesia* **36**, 287-298. https://doi.org/10.1111/j.1467-2995.2009.00459.x.

Qadan, M., Gardner, S.A., Vitale, D.S., Lominadze, D., Joshua, I.G. and Polk, H.C. (2009) Hypothermia and surgery. *Annals of Surgery* **250**, 134-140. https://doi.org/10.1097/sla.0b013e3181ad85f7.

Rainger, J., Dart, C. and Perkins, N. (2010) Factors affecting the relationship between arterial and end-tidal carbon dioxide pressures in the anaesthetised horse. *Australian Veterinary Journal* **88**, 13-19. https://doi.org/10.1111/j.1751-0813.2009.00535.x.

Reichert, C., Kästner, S.B.R., Hopster, K., Rohn, K. and Rötting, A.K. (2014) Use of micro-lightguide spectrophotometry for evaluation of microcirculation in the small and large intestines of horses without gastrointestinal disease. *American Journal of Veterinary Research* **75**, 990-996. https://doi.org/10.2460/ajvr.75.11.990.

Robertson, S.A. (2005) Sedation and general anaesthesia of the foal. *Equine Veterinary Education* **15**, 94-101.

Rousseau-Blass, F., Pigé, C. and Pang, D.S.J. (2020) Agreement between invasive and oscillometric arterial blood pressure measurements using the LifeWindow multiparameter monitor and two cuff sizes in anesthetized adult horses. *Veterinary Anaesthesia and Analgesia* **47**, 315-322. https://doi.org/10.1016/j.vaa.2020.01.001.

Russold, E., Ambrisko, T.D., Schramel, J.P., Auer, U., Hoven, R.V.D. and Moens, Y.P. (2013) Measurement of tidal volume using Respiratory Ultrasonic Plethysmography in anaesthetized, mechanically ventilated horses. *Veterinary Anaesthesia and Analgesia* **40**, 48-54. https://doi.org/10.1111/j.1467-2995.2012.00751.x.

Sacks, M. and Mosing, M. (2016) Volumetric capnography to diagnose venous air embolism in an anaesthetised horse. *Veterinary Anaesthesia and Analgesia* **44**, 189-190. https://doi.org/10.1111/vaa.12383.

Sasaki, N., Hobo, S. and Yoshihara, T. (1999) Measurement for breath concentration of hydrogen and methane in horses. *Journal of Veterinary Medical Science* **61**, 1059-1062. https://doi.org/10.1292/jvms.61.1059.

Schauvliege, S., den Eede, A.V., Duchateau, L., Pille, F., Vlaminck, L. and Gasthuys, F. (2009) Comparison between lithium dilution and pulse contour analysis techniques for cardiac output measurement in isoflurane anaesthetized ponies: influence of different inotropic drugs. *Veterinary Anaesthesia and Analgesia* **36**, 197-208.

Schneider, G., Gelb, A.W., Schmeller, B., Tschakert, R. and Kochs, E. (2003) Detection of awareness in surgical patients with EEG-based indices—bispectral index and patient state index. *British Journal of Anaesthesia* **91**, 329-335. https://doi.org/10.1093/bja/aeg188.

Schramel, J.P., Wimmer, K., Ambrisko, T.D. and Moens, Y.P. (2014) A novel flow partition device for spirometry during large animal anaesthesia. *Veterinary Anaesthesia and Analgesia* **41**, 191-195. https://doi.org/10.1111/vaa.12099.

Seavell, C. (2005) Measurement of gas concentrations. *Anaesth Intensive Care Medicine* **6**, 407-410. https://doi.org/10.1383/anes.2005.6.12.407.

Secombe, C., Waldmann, A.D., Hosgood, G. and Mosing, M. (2019) Evaluation of histamine-provoked changes in airflow using electrical impedance tomography in horses. *Equine Veterinary Journal* **52**, 556-563. https://doi.org/10.1111/evj.13216.

Senior, J.M., Pinchbeck, G.L., Allister, R., Dugdale, A.H.A., Clark, L., Clutton, R.E. et al. (2007) Reported morbidities following 861 anaesthetics given at four equine hospitals. *The Veterinary Record* **160**, 407-408. https://doi.org/10.1136/vr.160.12.407.

Shih, A. (2013) Cardiac Output Monitoring in Horses. *The Veterinary Clinics of North America. Equine Practice* **29**, 155-167. https://doi.org/10.1016/j.cveq.2012.11.002.

Shih, A.C., Giguère, S., Sanchez, L.C., Valverde, A., Jankunas, H.J. and Robertson, S.A. (2009) Determination of cardiac output in anesthetized neonatal foals by use of two pulse wave analysis methods. *American Journal of Veterinary Research* **70**, 334-339. https://doi.org/10.2460/ajvr.70.3.334.

Smale, K., Anderson, L.S. and Butler, P.J. (1994) An algorithm to describe the oxygen equilibrium curve for the Thoroughbred racehorse. *Equine Veterinary Journal* **26**, 500-502. https://doi.org/10.1111/j.2042-3306.1994.tb04058.x.

Snyder, J.R., Pascoe, J.R., Meagher, D.M. and Thurmond, M.C. (1994) Surface oximetry for intraoperative assessment of colonic viability in horses. *Journal of the American Veterinary Medical Association* **204**, 1786-1789.

Sorenson, P.R. and Robinson, N.E. (1980) Postural effects on lung volumes and asynchronous ventilation in anesthetized horses. *Journal of Applied Physiology* **48**, 97-103. https://doi.org/10.1152/jappl.1980.48.1.97.

Steffey, E.P., Howland, D. Jr, Giri, S., Eger, E.I. (1977) Enflurane, halothane, and isoflurane potency in horses. *American Journal of Veterinary Research* **38**, 1037-1039.

Steffey, E.P., Mama, K.R., Galey, F.D., Puschner, B. and Woliner, M.J. (2005) Effects of sevoflurane dose and mode of ventilation on cardiopulmonary function and blood biochemical variables in horses. *American Journal of Veterinary Research* **66**, 606-614.

Taylor, A.H. and Seymour, C.J. (2016) Effect of low inspired oxygen fraction on respiratory indices in mechanically ventilated horses anaesthetised with isoflurane and medetomidine constant rate infusion. *The Veterinary Journal* **211**, 70-74. https://doi.org/10.1016/j.tvjl.2016.02.011.

Taylor, P. and Clarke, K.W. (2007a) Chapter 4 - Inhalational Anaesthesia. *Handbook of Equine Anaesthesia*, 2nd edn., Saunders Elsevier, Philadelphia, PA. pp 55-85.

Taylor, P. and Clarke, K.W. (2007b) Chapter 5 - Monitoring. *Handbook of Equine Anaesthesia*, 2nd edn., Saunders Elsevier, Philadelphia, PA. pp 87-104.

Tearney, C.C., Guedes, A.G.P. and Brosnan, R.J. (2016) Equivalence between invasive and oscillometric blood pressures at different anatomic locations in healthy normotensive anaesthetised horses. *Equine Veterinary Journal* **48**, 357-361. https://doi.org/10.1111/evj.12443.

Tendillo, F.J., Mascias, A., Santos, M., Lopez-Sanroman, J., Rossi, R.D., Roman, F.S. and et al. (1997) Anaesthetic potency of desflurane in the horse: determination of the minimum alveolar concentration. *Veterinary Surgery* **26**, 354-357. https://doi.org/10.1111/j.1532-950X.1997.tb01511.x.

Thompson, K.R. and Bardell, D. (2016) The effect of two different intra-operative end-tidal carbon dioxide tensions on apnoeic duration in the recovery period in horses. *Veterinary Anaesthesia and Analgesia* **43**, 163-170. https://doi.org/10.1111/vaa.12277.

Tomasic, M. (1999) Temporal changes in core body temperature in anesthetized adult horses. *American Journal of Veterinary Research* **60**, 556-562.

Tomasic, M. and Nann, L.E. (1999) Comparison of peripheral and core temperatures in anesthetized horses. *American Journal of Veterinary Research* **60**, 648-651.

Trim, C.M. (1998) Monitoring during general anaesthesia: techniques and interpretation. *Equine Veterinary Education* **10**, 207-218. https://doi.org/10.1111/j.2042-3292.2005.tb01825.x.

Trim, C.M. and Wan, P.Y. (1990) Hypoxaemia during anaesthesia in seven horses with colic. *Veterinary Anaesthesia and Analgesia* **17**, 45-49. https://doi.org/10.1111/j.1467-2995.1990.tb00390.x.

Tünsmeyer, J., Hopster, K., Feige, K. and Kästner, S.B. (2015) Agreement of high definition oscillometry with direct arterial blood pressure measurement at different blood pressure ranges in horses under general anaesthesia. *Veterinary Anaesthesia and Analgesia* **42**, 286-291. https://doi.org/10.1111/vaa.12203.

Turner, P.G., Dugdale, A., Young, I.S. and Taylor, S. (2008) Portable mass spectrometry for measurement of anaesthetic agents and methane in respiratory gases. *The Veterinary Journal* **177**, 36-44. https://doi.org/10.1016/j.tvjl.2007.03.017.

Tutunaru, A., Dupont, J., Gougnard, A., Ida, K., Serteyn, D. and Sandersen, C. (2019) Retrospective evaluation of clinical use of cis-atracurium in horses. *PLoS One* **14**, e0221196. https://doi.org/10.1371/journal.pone.0221196.

Voulgaris, D.A. and Hofmeister, E.H. (2009) Multivariate analysis of factors associated with post-anesthetic times to standing in isoflurane-anesthetized horses: 381 cases. *Veterinary Anaesthesia and Analgesia* **36**, 414-420. https://doi.org/10.1111/j.1467-2995.2009.00472.x.

Walder, B., Lauber, R. and Zbinden, A.M. (1993) Accuracy and cross-sensitivity of 10 different anesthetic gas monitors. *Journal of Clinical Monitoring* **9**, 364-373. https://doi.org/10.1007/BF01618679.

Walton, T.E.F. and Wilson, M. (2017) Principles of pressure transducer function and sources of error in clinical use. *Anaesth Intensive Care Medicine* **18**, 581-585. https://doi.org/10.1016/j.mpaic.2020.10.008.

Watson, Z.E., Steffey, E.P., Van Hoogmoed, L.M. and Snyder, J.R. (2002) Effect of general anesthesia and minor surgical trauma on urine and serum measurements in horses. *American Journal of Veterinary Research* **63**, 1061-1065. https://doi.org/10.2460/ajvr.2002.63.1061.

Williams, D.C., Aleman, M.R., Brosnan, R.J., Fletcher, D.J., Holliday, T.A., Tharp, B. et al. (2016) Electroencephalogram of Healthy Horses During Inhaled Anesthesia. *Journal of Veterinary Internal Medicine* **30**, 304-308. https://doi.org/10.1111/jvim.13613.

Xu, H., Wang, Z., Guan, X., Lu, Y., Malone, D.C., Salmon, J.W. et al. (2020) Safety of intraoperative hypothermia for patients: meta-analyses of randomized controlled trials and observational studies. *BMC Anesthesiology* **20**, https://doi.org/10.1186/s12871-020-01065-z.

Yamashita, K., Akashi, N., Katayama, Y., Uchida, Y., Umar, M.A., Itami, T. et al. (2009) Evaluation of Bispectral Index (BIS) as an Indicator of Central Nervous System Depression in Horses Anesthetized with Propofol. *Journal of Veterinary Medical Science* **71**, 1465-1471.

Zoff, A., Dugdale, A.H.A.D., Scarabelli, S. and Rioja, E. (2019) Evaluation of pulse co-oximetry® to determine haemoglobin saturation with oxygen and haemoglobin concentration in anaesthetised horses: a retrospective study. *Veterinary Anaesthesia and Analgesia* **46**, 452-457. https://doi.org/10.1016/j.vaa.2019.02.005.

Advertisers' Index

EQUINE VETERINARY EDUCATION
Equine vet. Educ. (2022) **34** (12) 660-672
doi: 10.1111/eve.13627

Review Article

Epidemiology of exertional heat illness in Thoroughbred racehorses in temperate eastern Australia: The role of extrinsic (environmental) factors in disease causation

***M. Brownlow*[†,*] *and J. X. Mizzi*[‡]**

[†]*Racing Australia, Sydney, New South Wales, Australia; and* [‡]*Department of Regulation, Welfare and Biosecurity Policy, The Hong Kong Jockey Club, Sha Tin Racecourse, Hong Kong, Sha Tin, China*
**Corresponding author email: mbro8605@uni.sydney.edu.au*

Keywords: horse; exertional heat illness; epidemiology of exertional heat illness; Thoroughbred racehorses; extrinsic (environmental) risk factors; ambient temperature; radiant heat; vapour pressure (absolute humidity); wind speed

Summary

A simple epidemiological model of disease causation is proposed for exertional heat illness (EHI) in Thoroughbred racehorses. The agent of disease causation that must be present for the condition to occur is strenuous exercise, producing substantial quantities of metabolic heat. This is stored during racing but must be dissipated rapidly in the post-race period to prevent core body temperature rising to a critical level and causing the clinical manifestations of EHI. Environmental factors are next in the epidemiological triad, and it is a common misconception that these are the direct cause of EHI. In fact, environmental conditions enable EHI by either diminishing the evaporative capacity of the environment or promoting internal heat gain. This article deals with the specific effects of the four thermal elements, separately and in combination, on individual thermo-effector mechanisms. The final component in the epidemiological triad is individual host factors. A critical premise of epidemiology is that conditions such as EHI may not occur randomly in a population but may be more likely to occur in some individuals due to the presence of certain factors that predispose them to the condition. For the purpose of assessing risk, it is not feasible to examine the balance between metabolic heat production and the intrinsic and extrinsic factors, which collectively determine each individual's heat stress response. Therefore, the measurement of environmental factors remains the only practical way of obtaining a credible risk assessment for EHI, so that effective countermeasures can be instigated and the welfare of our racehorses ensured.

Introduction

The simplest model of disease causation is the epidemiological triad, presented here as a model for EHI to make the understanding of this complex medical condition easier (see **Fig 1**). The agent of causation, which must be presented in all cases for the disease to manifest, is strenuous exercise, typified by the intense activity of racing. It generates substantial metabolic heat (Hodgson et al., 1990, 1993), which is stored (Geor et al., 2000) but must be dissipated to the environment in the immediate post-race period by physical heat exchange mechanisms to halt the potential rise in core temperature to critical levels. Although the horse has a superlative thermoregulatory capacity and can dissipate heat most efficiently by evaporation of sweat from the skin and secretions from the upper respiratory tract, certain environmental conditions impair this process, increasing the risk of EHI (Brownlow & Mizzi, 2022a, 2022b; Hodgson et al., 1990, 1993).

Individual EHI susceptibility documented in human subjects is considered multifactorial, the risk being greatest when multiple factors combine (Westwood et al., 2020). It is proposed here that environmental conditions act as a catalyst or an enabler to precipitate EHI. Note, however, that it also occurs in certain individuals on cooler days, so that extreme levels of heat and humidity are not an absolute prerequisite for EHI to occur. The question as to why some horses are affected and not others warrants further investigation.

The aim of this article was to describe the potential impact of each thermal element in isolation, then to consider their various combinations and how they might collectively impact individual thermo-effector mechanisms, thereby contributing to an understanding of how the weather imposes heat stress conditions.

Exertional heat illness is a significant welfare issue because the clinical manifestations can be severe, constituting a risk to handlers and horses. Thoroughbred racehorses would appear to be particularly at risk because of the extreme intensity of their exercise activity (Brownlow & Mizzi, 2022a; Hodgson et al., 1993). The only way to prepare for such events is to predict the likelihood of their occurrence by monitoring the weather conditions and putting in place mitigation strategies as required.

Prevalence rates for EHI vary greatly. In a retrospective study from South Africa over a period of 21 years there was an overall prevalence of 0.13% in 375,701 horses, but this increased to 1.1% when records of individual horses were examined, with 16% of horses showing more than one episode (MacDonald et al., 2008). Nomura et al. (2019) reported a 20-year retrospective prevalence rate of 0.04% with an upward trend of 0.08% between 2015 and 2018 amongst 975,247 starters. These researchers suggested that the increase in number of horses diagnosed with EHI may have resulted from increased levels of awareness, rather than an actual increase in case numbers. More recently, Brownlow and Brotherhood (2021) reported prevalence rates of 9.0% (437/4809) for Level 1 horses demonstrating the earliest prodromal signs and 0.4% (20/4809) for Levels 2 and 3, where horses were exhibiting signs of central nervous system involvement. It is clear that the case definition of EHI

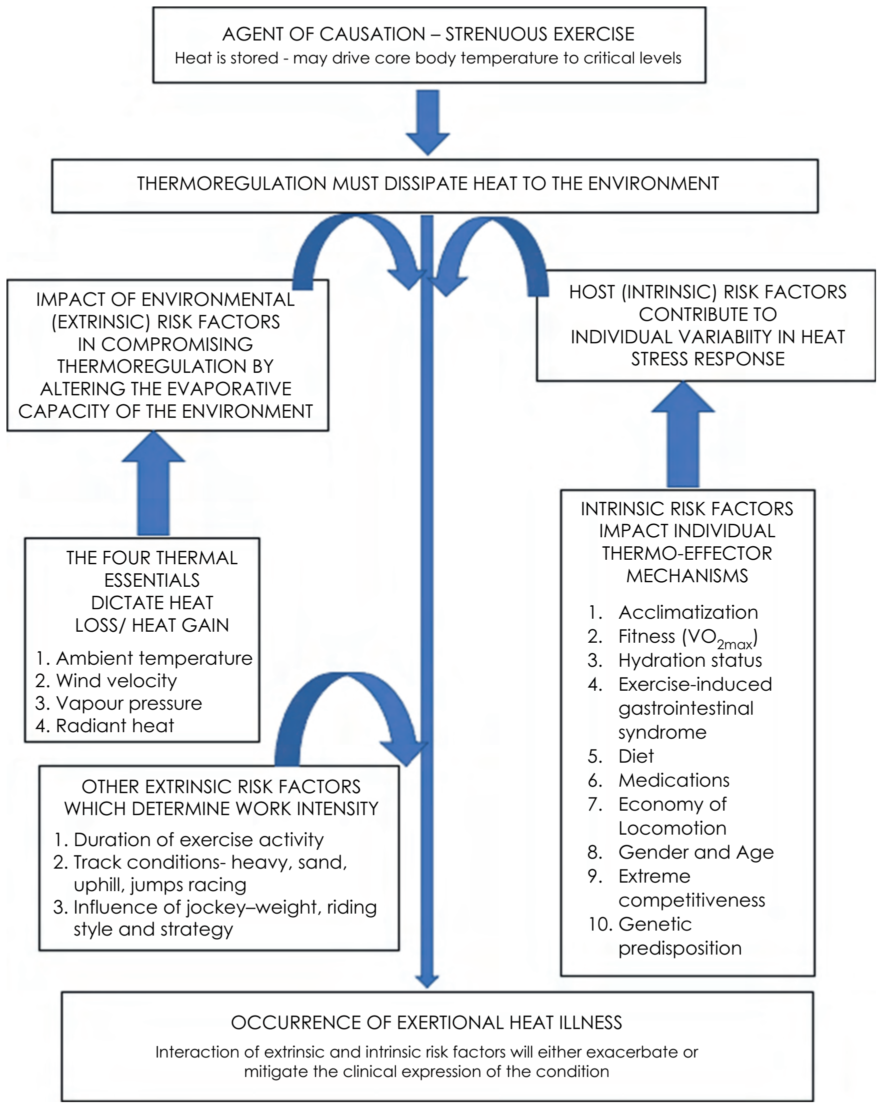


***Fig 1:** The epidemiological triad for exertional heat illness in the Thoroughbred racehorse, showing the proposed role of extrinsic and intrinsic risk factors, which may influence its occurrence.*

describing the earliest EHI signs and geographical context will affect prevalence rates accordingly, together with other factors such as inter-rater expertise. Notwithstanding which prevalence figures are the most accurate, post-race EHI has become a subject of growing concern for many racing jurisdictions and, with the possibility of global warming, may become the main welfare issue for horse racing in the coming decade.

The content of this article and its focus on the role of the essential thermal elements should assist on-track veterinarians to better understand the dynamic nature of the response to strenuous exercise in the context of climatic heat stress.

The hyperthermic response to strenuous exercise

During strenuous exercise, the principal source of heat acting on the animal's body is the metabolism associated with muscular contraction, which is largely independent of the thermal environment. Production of metabolic heat increases abruptly at the onset of exercise and is commensurate with exercise intensity and duration. Much of this heat is retained and distributed throughout the body, raising core body temperature (Geor et al., 2000; Jessen, 2000). The seminal work of Hodgson et al. (1993) showed that if all the metabolic heat was stored, the core body temperature of the racing Thoroughbred could increase by 0.8°C per minute, and temperatures of 42.0°C have commonly been reported in experimental treadmill studies without clinical manifestations of EHI (Butler et al., 1993; Weishaupt et al., 1996). The fact that EHI can occur in cooler or moderate weather conditions supports the concept that exercise heat production is the primary cause of the condition (Brownlow & Brotherhood, 2021).

Immediately after racing, environmental conditions dictate the efficiency of heat dissipation

Once the exercise activity has been completed, the production of metabolic heat decreases dramatically and there is a transitional stage where the primary source of 'thermal strain' changes from metabolic heat production to the influence of the environment on thermo-effector responses and the necessity for dissipation of the stored heat load. The skin surface becomes the focus for heat exchange (Jessen, 2000). Rises in skin temperature potentiate convective and evaporative heat loss, and the combination of high core and skin temperatures will provoke heavy sweating (Davies, 1979; Geor et al., 2000; McConaghy et al., 1995). The rate at which heat is lost, however, is almost entirely a function of the cooling power of the environment, which is influenced by the combined action of the environmental thermal elements: ambient temperature, radiant heat, water vapour pressure (humidity) and air flow over the skin surface (Brotherhood, 2008; Budd, 2001). Whilst each acts independently, they will have a combined effect in assisting or hindering thermoregulatory processes (Budd, 2001; Parsons, 2002).

The role of individual environmental thermal elements in the thermoregulatory process

Radiant heat

The sun is the source of radiant heat, and its effect on an animal represents the cumulative effects of direct, reflected and re-radiated solar radiation, the latter two emanating from surrounding surfaces (Parsons, 2002, 2006). High levels of solar radiation are common in hot and sunny climates and can elevate skin temperature by 1.5–2.0°C in human athletes (Otani et al., 2016, 2017) and horses (Guthrie & Lund, 1998). Such an increase in skin temperature potentially changes the dynamics of heat transfer, resulting in decreased heat loss and possibly a heat gain (Otani et al., 2021). Animals with darker coloured hair coats may also be more susceptible to radiative heat gains than those with lighter colours (McNicholl et al., 2016; Walsberg et al., 1978).

Practical approaches to minimise the effects of radiant heat

When the sun is obscured by cloud, the intensity of radiant heat falls. Similarly, shade provided on race day, where horses congregate will shield them from radiant heat. Also, the sun's progressive change in position during the day results in fluctuating levels of radiant heat (Blazeiczyk et al., 1999), and this can be used to advantage by changing the times of racing to correspond with the lower levels. In the 6 h around midday, radiative heat from the sun is at its peak and Otani et al. (2016); Otani et al. (2017); Otani et al. (2019) recorded increasing radiant heat intensity from 09.00 h, peaking at noon and decreasing thereafter, so that racing in the later afternoon and into the night avoids the period of highest radiant heat. Mean radiant temperature (MRT°C) is the meteorological measurement of radiant heat, and during hot days in the Australian summer months in some areas, readings of 60°C–70°C, which may be approximately 30°C above ambient temperature levels, are commonly observed (Jay & Brotherhood, 2016).

Ambient temperature

Ambient temperature determines the skin-to-air temperature difference, which dictates whether 'dry' heat transfer can operate, where convective and radiative heat exchanges are the major mechanism, or whether the production and evaporation of sweat is required to cool effectively (Brotherhood, 2008; Jessen, 2000). **Figure 2** shows the important relationship between skin temperature and air temperature. At cooler air temperatures (<35°C), skin temperature is usually higher than air temperature, so that heat is readily lost through convective/radiative heat exchange and the body is cooled; but at higher air temperatures, (>38.0°C) skin temperature is exceeded and convective/radiative heat exchange reverses, potentially adding heat to the body (Sawka & Young, 2006). At this point, evaporative cooling must compensate for any additional heat gain due to high ambient temperature, as well as dissipating the metabolic heat stored from exercise activity (Brotherhood, 2008; Parsons, 2002).

Vapour pressure (absolute humidity)

Horses have been described as having the highest sweating rate in the animal kingdom (Jessen, 2000; McCutcheon & Geor, 1998, 2008) and this is considered the major route of heat loss, but they are also able to dissipate large quantities of heat through the respiratory tract by adopting a panting type of respiration (Brownlow & Mizzi, 2022a; Hodgson et al., 1993). The physical mechanism of evaporative cooling is similar for both pathways, with the vaporisation of fluid from sweat and respiratory secretions resulting in cooling as the heated vapour is transferred to the environment (Jessen, 2000). To understand the risk of EHI, it must be appreciated that environmental evaporative conditions vary, depending upon the level of humidity, and evaporative cooling works best in conditions of low humidity. High humidity impairs

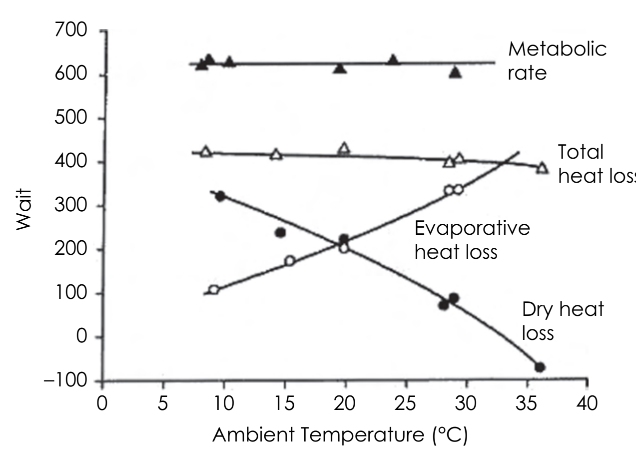


Fig 2: ***Showing that the relative contributions of convective or 'dry' heat loss and evaporative heat loss to total heat loss is entirely dependent on environmental conditions. When horses race in cool conditions (15–20.0°C), their skin temperatures (30–33.0°C) are greater than air temperature, and convective and radiative heat exchanges alone will dissipate much of their heat load. However, at higher air temperatures (>35.0°C) the skin-to-air temperature difference is smaller and convection is reduced, so that heat loss becomes increasingly dependent on the production and evaporation of sweat. Convective cooling becomes negligible at air temperatures around 36.0°C and beyond this point, convective heat exchange reverses and heat is added to the body instead of being lost. The rate of convective cooling is also profoundly influenced by air movement over the skin surface (Image with permission of Dr Michael Sawka, 2011).***

evaporative cooling and horses so affected may be seen with sweat dripping from the body onto the ground. A diagrammatic representation of the evaporative process associated with sweating is shown in **Figure 3a** and a photograph showing vaporisation of sweat after a strenuous workout to a still environment in **Figure 3b**.

The terminology of atmospheric moisture – relative humidity vs. vapour pressure

'Humidity' refers to the water vapour content of the air. Relative humidity (RH%) is the term most used in weather forecasts but is the most misleading and misunderstood humidity variable (Davis et al., 2016). Usually expressed as a percentage, it is the ratio between the amount of water vapour present in the air and the saturation value at the same temperature.

Put simply, RH% represents the extent to which the air is saturated. Scrutiny of its calculation, however, reveals that whilst the numerator depends on humidity the denominator varies with air temperature. This means that relative humidity can change quite markedly, whilst the air's actual moisture (the number of water vapour molecules) remains constant. RH% is highest when the air is close to saturation, which usually happens in the early morning and in winter. Thus, RH% typically declines towards the hottest part of the day because it is inversely proportional to ambient temperature (Davis et al., 2016).

The term 'vapour pressure' correlates closely to absolute humidity (Davis et al., 2016) and is associated with the evaporative capacity of the environment, which is of greatest interest to race-day veterinarians because it directly relates to the dissipation of heat and the efficiency of cooling. Generally, vapour pressure remains constant in any 12-h period, so that predicted levels for a given race day are unlikely to change significantly. It is most important for users of weather information to appreciate that because RH% depends on both humidity and temperature, its use is limited in any heat stress evaluation where the objective is to ascertain the specific impact of individual environmental variables. Unlike vapour pressure, relative humidity is not directly related to the evaporative capacity of the environment, so is neither reliable nor useful as a guide to the risk of EHI (Brotherhood, 2008; Brownlow & Brotherhood, 2021).

To illustrate these concepts, an example of the differences between vapour pressure and the vagaries of RH % are shown in **Figure 4a,b**, from Jay and Brotherhood (2016). These figures provide a useful illustration for those readers not familiar with the behaviour of the essential thermal elements over a 12-h period. Panel a covers a typical working day from 06:00 to 18:00 in a hot, sunny environment, but indoors, whilst Panel b is outdoors. In Panel a, radiant heat approximates ambient temperature because the location is out of direct sunlight. Predictably, air temperature increases as the working day progresses, with peak values attained between 14:00 and 16:00 h in both examples. Panel b shows that radiant heat in the outdoor setting peaks closer to 12:00. Radiant heat level is 45°C in the shearing shed, compared with 70.0°C outdoors. These observations demonstrate the importance of accounting for radiant heat sources when evaluating the risk of EHI where horses race in hot, sunny climates. It is also important to observe the comparative changes in relative humidity. RH% falls as the temperature rises, yet vapour pressure (absolute humidity), the more important measurement for evaporative cooling, remains approximately constant. It can be appreciated from these graphs that the changes to RH% can mislead those monitoring only RH% in the race-day setting. In stable weather, vapour pressure or absolute humidity level (Pa; Pw) remains fairly constant throughout the day and may be predicted from weather forecasting sites using a mobile phone with a simple app. https://www.vaisala.com/en/lp/humidity-calculator or monitored on-site using a hand-held device (Humicap HM70, Vaisala Corporation).

Air flow over the skin surface increases both convective and evaporative cooling

The important effects of air flow have been demonstrated in human athletes in the laboratory (see **Fig 5**). Saunders et al. (2005) showed that when there was zero air flow, cyclists exercising strenuously in warm and humid conditions experienced excessive levels of heat storage, resulting in elevations to core body temperature. When an air flow of 2.8 m/s was introduced, heat storage fell, due to the initiation of effective thermoregulation. Increasing air flow above 9.0 metres per second, however, produced a non-linear response, suggesting that once a certain wind speed was reached, other factors pertaining to the thermoregulatory limitations of the body became more relevant.

Air flow over the skin surface alters the immediate thermal environment, dispersing the hot air and vapourised sweat close to the skin and simultaneously increasing the rates of convection and evaporation, thereby accelerating heat loss to the environment. However, it is not only wind speed that affects heat loss but also the temperature of the moving air. A cooler wind will accelerate convective heat loss by increasing the convective gradient and, conversely, a warmer wind may have the reverse effect (Brotherhood, 2008; Budd, 2001).

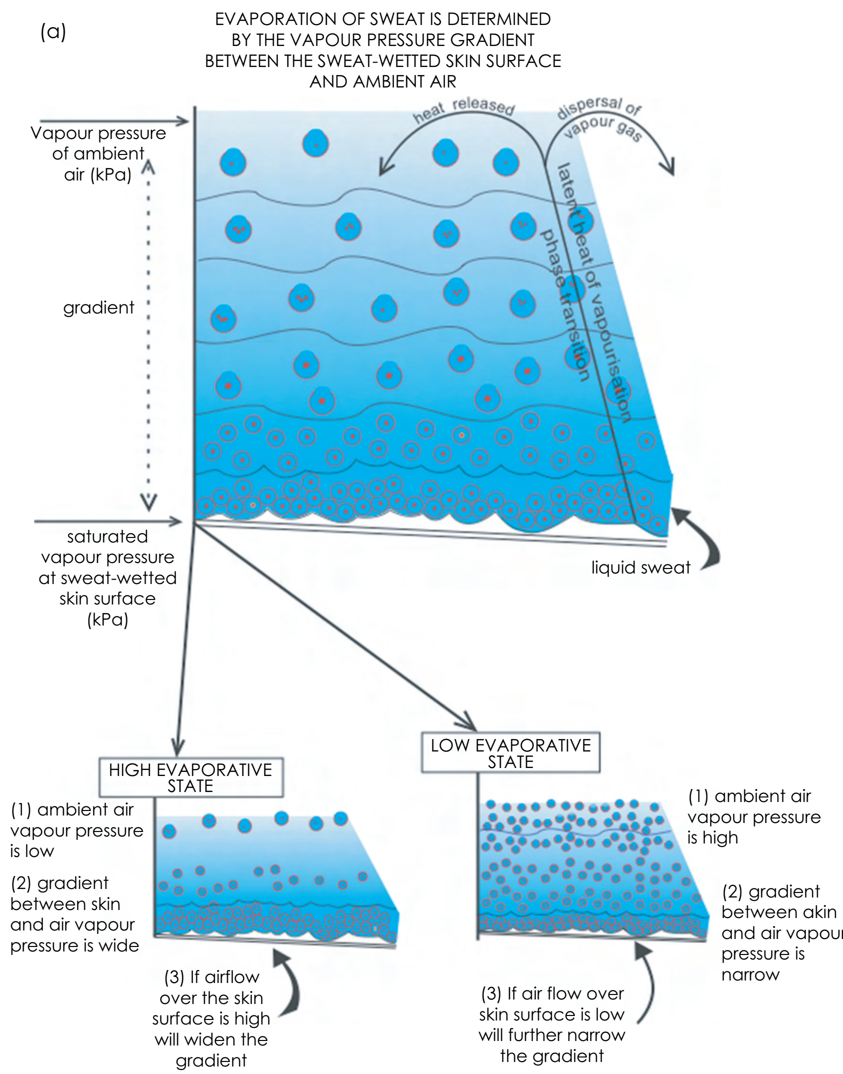
Environmental conditions associated with EHI in temperate eastern Australia

From 2014 to 2018, Brownlow and Brotherhood (2021) carried out an observational study to investigate environmental risk factors associated with the occurrence of EHI. Thermal environmental data were measured, including ambient temperature, radiant heat, vapour pressure (humidity) and wind speed, and cases of EHI were collected from amongst 4809 starters at 78 race meetings. Mixed linear regression models were computed to assess the association between the incidence of post-race EHI and the four thermal environmental variables. Analysis showed that vapour pressure and wind speed had the largest effects on the occurrence of post-race EHI.

High ambient temperature, low levels of vapour pressure, variable wind speeds

There were 23 days on which cases of EHI were observed. Six of those days were classified as 'hot', typically with high levels of radiant heat, and ambient temperatures ranging between 36.5°C and 41.0°C. Most importantly, vapour pressure levels were low (0.9–1.5 kPa) and wind speed was variable. Horses tolerated these conditions well because sweat evaporated freely and heat transfer from the body to the environment was efficient on most occasions. The key determinant on

(a)


EVAPORATION OF SWEAT IS DETERMINED BY THE VAPOUR PRESSURE GRADIENT BETWEEN THE SWEAT-WETTED SKIN SURFACE AND AMBIENT AIR
Vapour pressure of ambient air (kPa)
gradient
saturated vapour pressure at sweat-wetted skin surface (kPa)
heat released
dispersal of vapour gas
latent heat of vapourisation
phase transition
liquid sweat
HIGH EVAPORATIVE STATE
(1) ambient air vapour pressure is low
(2) gradient between skin and air vapour pressure is wide
(3) If airflow over the skin surface is high will widen the gradient
LOW EVAPORATIVE STATE
(1) ambient air vapour pressure is high
(2) gradient between akin and air vapour pressure is narrow
(3) If air flow over skin surface is low will further narrow the gradient

(b)

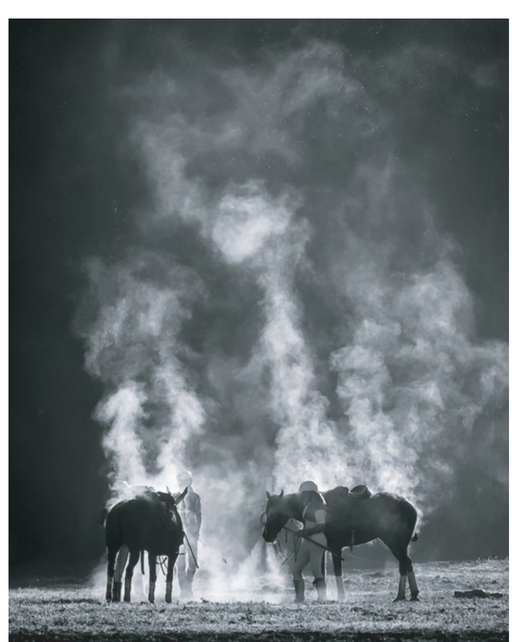


***Fig 3:** (a) First, sweat has to be produced then it must be evaporated to cool the body. Evaporation is a two-step process involving the phase transition of sweat on the skin surface from liquid to vapour (latent heat transfer), followed by the diffusion of vapour into the surrounding air, which diminishes with increasing humidity. Sweat evaporates freely when the ambient air pressure is low and the gradient from the skin surface to air is wide; but evaporation is impeded when the ambient air pressure is high and the gradient is narrow. Air movement over the skin surface has a substantial impact on evaporation and higher air velocities increase evaporative heat transfer. (b) Clouds of water vapour surround this group of horses, sweating after strenuous early morning exercise. The formation of fine droplets in the cool, still air renders the vapour visible, providing a graphic illustration of the heat dissipation process. Heat-laden moisture from respiratory secretions can be seen in the exhaled breath of the horse in the immediate foreground. An atmosphere of low evaporative capacity would hinder this process, causing the sweat to remain on the skin or drip off onto the ground. (Image courtesy of Dr E Lim, Camden, NSW, Australia).*

these days for emergent EHI was wind speed, and cases most commonly occurred when there were calm or 'wind-still' conditions. Horses competing in 'hot' conditions tended to have high skin temperatures into the recovery period, usually >39.0°C, as measured by infrared thermometer (Brownlow & Smith, 2020). These horses were prioritised as 'at risk' of EHI and were aggressively cooled, the aim being to decrease skin temperature with iced water, which potentiates the transfer of heat from a hot core to a cooler skin surface (Brownlow & Mizzi, 2022b). They responded with almost normal recoveries in terms of heart and respiratory rate, level of physiological strain and recovery time.

How hot is too hot?

Many racing jurisdictions have relied upon ambient temperature in isolation to answer this seemingly straightforward question, but it is problematic to put in place a maximum cut-off temperature. As previously discussed,

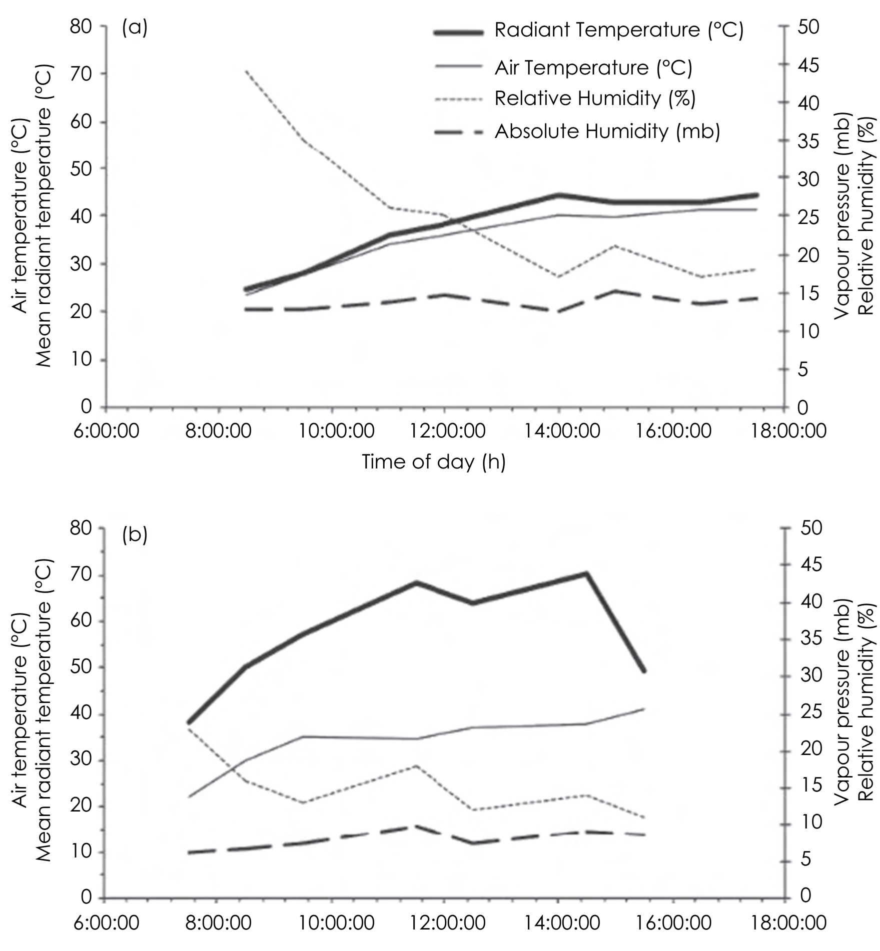


***Fig 4:** Variation in the elements of the thermal environment during working days in summer. Panel (a) is from a sheep shearing shed in South Australia; Panel (b) is from a railway worksite on the Nullarbor Plain in South Australia. Note that the term absolute humidity is used instead of vapour pressure. According to Davis et al. (2016), correlation between the humidity variables, vapour pressure and absolute humidity, is so high that they are virtually interchangeable (reproduced from Jay and Brotherhood [2016] with permission from Taylor & Francis [www.tandfonline.com]).*

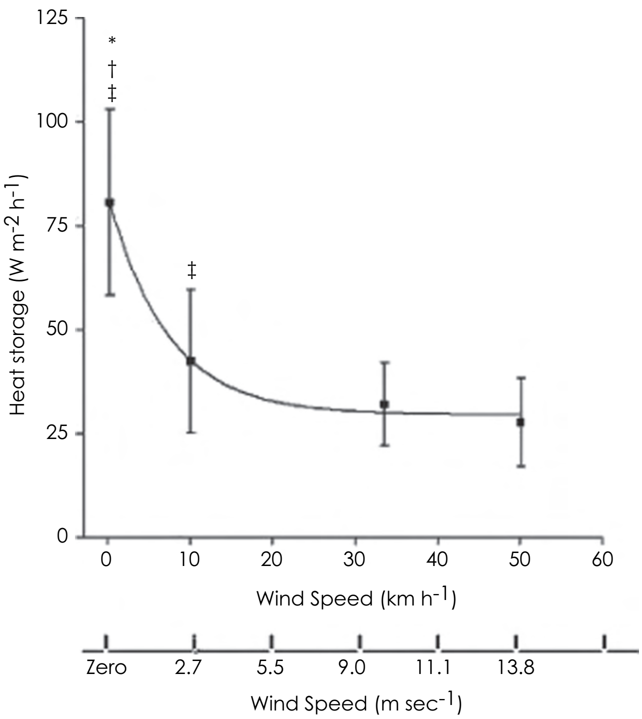


Fig 5: Measurements obtained from human subjects under laboratory conditions, showing the important effects of air flow. Calculated heat storage expressed per hour during trials with different air velocities. Heat storage over the course of the trial decreased significantly with increasing air velocity. Heat storage was significantly higher at zero air flow compared with other conditions (adapted from Saunders et al. [2005] with permission from John Wiley & Sons).

because hot conditions are almost always associated with low levels of vapour pressure, thermoregulatory mechanisms are not significantly impaired and horses cool effectively. Nevertheless, when environmental temperatures are >40.0°C, radiative and convective heat exchanges are reversed, heat is gained, and evaporative cooling must compensate for that extra heat, as well as the metabolic heat stored from racing. Wind speed will dictate the outcome in emergent cases of EHI.

TABLE 1: Levels of vapour pressure and proposed levels of risk

Level of risk	Low	Moderate	High	Extreme (perilous conditions)
Vapour pressure (kPa)	1.0–1.9	2.0–2.5	>2.5	>3.0

Note: that air flow >2.5 metres/s can negate the effects of high vapour pressure. Vapour pressure can be easily calculated from a mobile phone app. or with a hand-held monitoring device https://www.vaisala.com/en/lp/humidity-calculator.

TABLE 2: Wind speed and proposed levels of risk for exertional heat illness (EHI)

Level of risk	Low	Moderate	High	Extreme
Wind speed	>2.5 m/s	<2.5 m/s	<1.5 m/s	Wind-still or calm conditions

Wind speed is not always constant, and this will need to be factored into the EHI risk category.

Warm ambient temperatures, high levels of vapour pressure (humidity) and variable wind speeds

The second type of environmental condition commonly associated with EHI in our racing jurisdiction is that associated with high humidity. There were 17 days when the temperature ranged from 30.0° to 35.0°C, relative humidity varied between 50% and 80% and, most importantly, vapour pressure was above 2.5 kPa (Brownlow & Brotherhood, 2021). These conditions were considered to represent a high risk of EHI (see **Table 1**).

The problem with such days is that because the temperature is relatively low and most racing jurisdictions tend not to measure levels of vapour pressure, the risk associated with racing is underestimated. When vapour pressure levels are high, thermoregulatory capacity is impaired. In the post-race recovery period, horses were dripping with sweat, had elevated heart rates, and exhibited a panting type of respiration. Significantly, the recovery time in most cases was extended to at least 60 min and horses so

Fig 6: Examples of how variable wind speed affects the clinical expression of exertional heat illness (EHI). All wind speed measurements were taken in the vicinity of the race-day stalls where most cases of EHI occur. Venue (a): Hawk 19 November 2015: Mean ambient temperature: 39.3°C (maximum 41.5°C); Vapour Pressure 1.6 kPa; Relative Humidity 22.7%: MRT 63.3°C; WBGT 30.2°C; Clear and sunny. Mean wind speed 3.6 m/s; Breezy throughout the day. Few horses required aggressive cooling; most were just hosed and recovered in normal timeframes. Despite high ambient temperature and radiant heat levels, high wind speeds ensure evaporative cooling so that no aggressive cooling was required. Venue (b): Kembla Grange 27 January 2018: Mean ambient temperature 28.2°C; Vapour pressure 2.8 kPa; Relative Humidity 70.1%; MRT 42.8°C; WBGT 28.2°C. Scattered high cloud, strong breeze. Mean wind speed 4.7 m/s. Constant throughout the day. Despite high vapour pressure levels, all horses recovered well. Some horses required aggressive cooling. Despite high vapour pressure (2.8 kPa), high wind speeds enabled sufficient evaporative cooling, although a few horses required aggressive cooling. Venue (c): Hawkes 26 February 2016: Mean ambient temperature 38.0°C (maximum 40.4°C); Mean vapour pressure 2.9 kPa; Relative Humidity 44.7%; MRT 71.2°C; WBGT 32.1°C; Mean wind speed 0.8 m/s (Max = 2.3; Min = 0). Approximately 80% of horses required aggressive cooling; 2 horses escalated to Level 2 EHI, were treated and responded well. Although there was some wind out on the racetrack, in the race-day stalls, there was no perceptible breeze. High ambient temperature and radiant heat, high vapour pressure but no breeze, with a mean wind speed of 0.8 m/s. Most horses were distressed, many Level 1 horses, some escalating to Level 2 and all slow to recover. Venue (d): Warwick Farm 22 March 2017: Mean ambient temperature 31.2°C (maximum 36.6°C); Mean vapour pressure 2.6 kPa; Relative Humidity 57.6%; MRT 49.0°C; WBGT 30.0°C; Mean wind speed 0.6 m/s; (Max = 1.9; Min = 0). Horses were distressed and dripping with sweat, many requiring aggressive cooling. One horse escalated to level 2 EHI. High levels of vapour pressure together with low wind speeds predisposed horses to EHI.

UNITED STATES POSTAL SERVICE® Statement of Ownership, Management, and Circulation (All Periodicals Publications Except Requester Publications)

1. Publication Title	2. Publication Number	3. Filing Date
Equine Veterinary Education	0 1 8 - 2 2 7	10/12/22
4. Issue Frequency	**5. Number of Issues Published Annually**	**6. Annual Subscription Price**
Monthly	12	$151.80

7. Complete Mailing Address of Known Office of Publication (*Not printer*) (*Street, city, county, state, and ZIP+4®*)
AAEP
4033 Iron Works Pkwy
Lexington, KY 40511

Contact Person: David Foley
Telephone (*Include area code*): (859) 233-0147

8. Complete Mailing Address of Headquarters or General Business Office of Publisher (*Not printer*)
Same

9. Full Names and Complete Mailing Addresses of Publisher, Editor, and Managing Editor (*Do not leave blank*)

Publisher (*Name and complete mailing address*)
Same

Editor (*Name and complete mailing address*)
David Foley, AAEP, 4033 Iron Works Pkwy, Lexington, KY 40511

Managing Editor (*Name and complete mailing address*)
Same

10. Owner (*Do not leave blank. If the publication is owned by a corporation, give the name and address of the corporation immediately followed by the names and addresses of all stockholders owning or holding 1 percent or more of the total amount of stock. If not owned by a corporation, give the names and addresses of the individual owners. If owned by a partnership or other unincorporated firm, give its name and address as well as those of each individual owner. If the publication is published by a nonprofit organization, give its name and address.*)

Full Name	Complete Mailing Address
American Association of Equine Practitioners	4033 Iron Works Pkwy Lexington, KY 40511

11. Known Bondholders, Mortgagees, and Other Security Holders Owning or Holding 1 Percent or More of Total Amount of Bonds, Mortgages, or Other Securities. If none, check box → ☑ None

Full Name	Complete Mailing Address

12. Tax Status (*For completion by nonprofit organizations authorized to mail at nonprofit rates*) (*Check one*)
The purpose, function, and nonprofit status of this organization and the exempt status for federal income tax purposes:
☑ Has Not Changed During Preceding 12 Months
☐ Has Changed During Preceding 12 Months (*Publisher must submit explanation of change with this statement*)

13. Publication Title	14. Issue Date for Circulation Data Below	
Equine Veterinary Education	August 2022	
15. Extent and Nature of Circulation	**Average No. Copies Each Issue During Preceding 12 Months**	**No. Copies of Single Issue Published Nearest to Filing Date**
a. Total Number of Copies (*Net press run*)	6,659	7,850
b. Paid Circulation (*By Mail and Outside the Mail*) (1) Mailed Outside-County Paid Subscriptions Stated on PS Form 3541 (Include paid distribution above nominal rate, advertiser's proof copies, and exchange copies)	5,754	6,801
(2) Mailed In-County Paid Subscriptions Stated on PS Form 3541 (*Include paid distribution above nominal rate, advertiser's proof copies, and exchange copies*)	0	0
(3) Paid Distribution Outside the Mails Including Sales Through Dealers and Carriers, Street Vendors, Counter Sales, and Other Paid Distribution Outside USPS®	0	0
(4) Paid Distribution by Other Classes of Mail Through the USPS (e.g., First-Class Mail®)	747	877
c. Total Paid Distribution (*Sum of 15b (1), (2), (3), and (4)*)	6,501	7,678
d. Free or Nominal Rate Distribution (*By Mail and Outside the Mail*) (1) Free or Nominal Rate Outside-County Copies included on PS Form 3541	0	0
(2) Free or Nominal Rate In-County Copies Included on PS Form 3541	0	0
(3) Free or Nominal Rate Copies Mailed at Other Classes Through the USPS (e.g., First-Class Mail)	0	0
(4) Free or Nominal Rate Distribution Outside the Mail (*Carriers or other means*)	50	50
e. Total Free or Nominal Rate Distribution (*Sum of 15d (1), (2), (3) and (4)*)	50	50
f. Total Distribution (*Sum of 15c and 15e*)	6,551	7,728
g. Copies not Distributed (*See Instructions to Publishers #4 (page #3)*)	108	122
h. Total (*Sum of 15f and g*)	6,659	7,850
i. Percent Paid (*15c divided by 15f times 100*)	99.2	99.4

* If you are claiming electronic copies, go to line 16 on page 3. If you are not claiming electronic copies, skip to line 17 on page 3.

UNITED STATES POSTAL SERVICE® Statement of Ownership, Management, and Circulation (All Periodicals Publications Except Requester Publications)

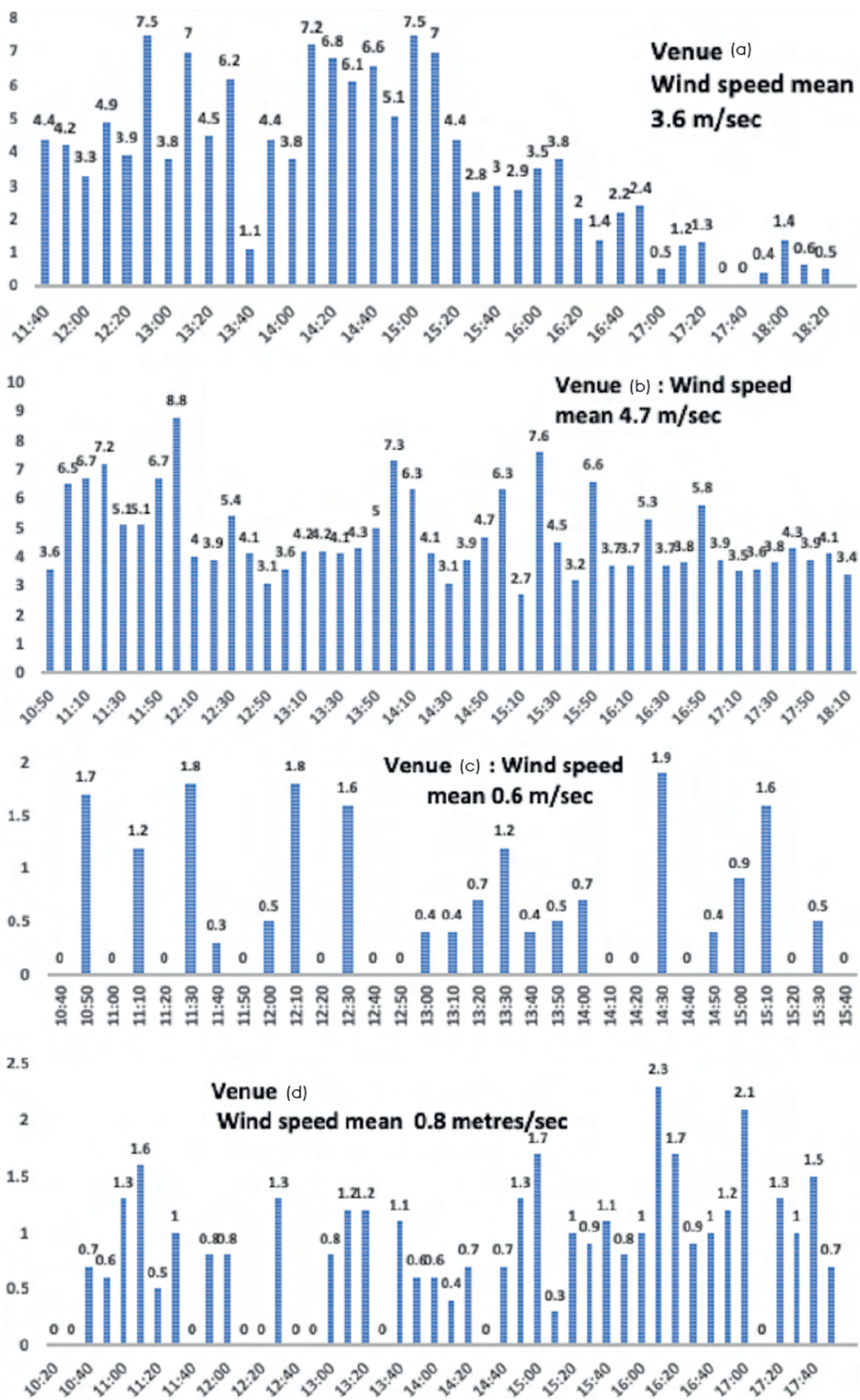
16. Electronic Copy Circulation	Average No. Copies Each Issue During Preceding 12 Months	No. Copies of Single Issue Published Nearest to Filing Date
a. Paid Electronic Copies		
b. Total Paid Print Copies (Line 15c) + Paid Electronic Copies (Line 16a)		
c. Total Print Distribution (Line 15f) + Paid Electronic Copies (Line 16a)		
d. Percent Paid (Both Print & Electronic Copies) (16b divided by 16c × 100)		

☐ I certify that 50% of all my distributed copies (electronic and print) are paid above a nominal price.

17. Publication of Statement of Ownership
☑ If the publication is a general publication, publication of this statement is required. Will be printed in the December 2022 issue of this publication. ☐ Publication not required.

18. Signature and Title of Editor, Publisher, Business Manager, or Owner | Date

I certify that all information furnished on this form is true and complete. I understand that anyone who furnishes false or misleading information on this form or who omits material or information requested on the form may be subject to criminal sanctions (including fines and imprisonment) and/or civil sanctions (including civil penalties).


Venue (a)
Wind speed mean
3.6 m/sec
Venue (b) : Wind speed
mean 4.7 m/sec
Venue (c) : Wind speed
mean 0.6 m/sec
Venue (d)
Wind speed mean 0.8 metres/sec

affected were classified in race-day reporting as 'slow to recover', reflecting substantial levels of thermal strain due to the redistributive effects of cardiac output. Horses required aggressive levels of cooling, multiple cooling strategies were often required, and cooling times were generally protracted. In such conditions, horses need to be scraped at the end of the cooling procedure because neither water nor sweat could evaporate effectively from the skin surface. The use of large dry fans increases evaporative cooling in these situations.

Air flow dynamics at the racetrack

At the racetrack, when heat and/or humidity levels are high, Brownlow and Brotherhood (2021) reported that air flow becomes the determining factor for emergent EHI, with 'wind-still' or calm conditions representing extreme levels of risk (see **Table 2**).

Despite the importance of wind speed, it is the most fickle of all the thermal elements. **Figure 6a–d** shows examples from different venues of how variable wind speeds can affect the clinical expression of EHI. Note that the *X*-axis represents wind speed in metres/second and the *Y*-axis represents time.

Wind speed can be very unpredictable, varying in time, direction and from location to location. A sudden drop in wind speed can transform an uneventful race day into one on which numerous horses become heat-affected. Cases of EHI most commonly occur after racing and in the 'tie-up' stalls, which tend to be sheltered areas, characterised by 'wind-still' conditions. These areas may in effect have their own microclimate, with different and changeable evaporative conditions compared with the more open racing and parading areas. Low wind speeds severely compromise evaporative cooling and intermittent wind speeds below 1.5 m/s are likely to precipitate EHI. In contrast, wind speeds greater than 2.5 to 3.0 m/s create excellent conditions for evaporative cooling and can even negate the effects of high vapour pressure (Brownlow & Brotherhood, 2021; Otani et al., 2018).

The use of the WBGT°C (wet-bulb globe temperature) for risk assessment of EHI

The WBGT was introduced in 1957 as part of a campaign to prevent heat-related deaths amongst military trainees in the US Army and Marine Corps (Yaglou & Minard, 1957). Since that time the WBGT has received widespread acceptance, been used during military, occupational, industrial and sporting activities and incorporated into heat policy recommendations by many high-profile human sporting organisations (Armstrong et al., 2017; Racinais et al., 2015). It has also been used for equestrian competitions (Jeffcott & Kohn, 1999; Jeffcott et al., 2009; Schroter et al., 1996) and forms part of heat policy guidelines for Thoroughbred, Standardbred and greyhound racing worldwide (McNicholl et al., 2016).

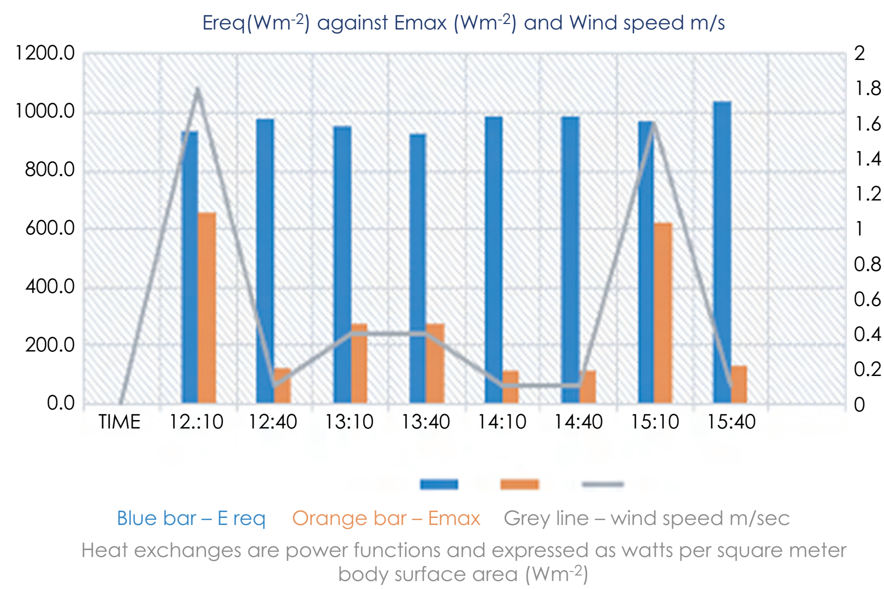
The WBGT is an empirical index based on three measurements, the dry bulb temperature, the natural wet-bulb temperature and the black-globe temperature. Whilst the WBGT does not directly measure air velocity, it is claimed that the effects of wind are reflected in the reading of the natural wet bulb, but it is generally acknowledged that this response is inadequate at low wind speeds and represents a serious shortcoming of the WBGT, particularly in very humid environments, so that some workers have totally revised levels for risk assessment if humidity is high (Casa et al., 2017; Periard et al., 2015; Sawka & Young, 2006). Recently, many thermal physiologists have expressed concern that the WBGT is still so widely used despite the expanding knowledge of its substantial limitations, specifically its failure to appropriately reflect the severity of adverse weather conditions (Brocherie et al., 2014; Brocherie & Millet, 2015; Budd, 2008; D'Ambrosio Alfano et al., 2014). Proponents reply to criticism by emphasising that the WBGT should not be used to establish participation cut-off values but rather to enable recommendations for implementing preventative countermeasures when the risk of EHI is deemed to be high (Periard et al., 2015).

Discussion

The epidemiological triad has been introduced as a means of understanding the complexity of EHI. It is commonly thought that the weather is the sole cause of the condition, through exposure of the animal to the direct effects of heat and humidity, but this is not always the case and other intrinsic factors which contribute to individual variability by acting on thermo-effector mechanisms will determine the heat stress response. Nevertheless, being able to predict the effect of weather on a given race day is a most important step in risk analysis and will form the basis of risk mitigation strategies.

Belding and Hatch (1955) developed a rational analysis of heat stress, where fundamental physical principles were used to estimate each of the avenues of heat exchange between the body and the environment (see **Fig 7**). Calculation of these exchanges indicated whether thermal balance and control of body temperature could be achieved in the prevailing environmental conditions. A simple conceptual application of this analysis can be quite useful for race-day veterinarians because it directly relates to clinical observations of horses in the post-race period and provides a framework for assessment of an individual animal's thermoregulatory processes.

The required rate of heat transfer for an individual animal to effectively cool is referred to as Ereq. This integrates metabolic heat production with evaporative, radiative and convective heat exchanges. On hot days, the contributions of radiative and convective losses diminish, even reversing and may become actual heat gain. It is clear that in the immediate post-race period, Ereq relies on the evaporative cooling provided by sweating and this depends not only on the production of sufficient sweat (Davies, 1979; Nielsen & Nielsen, 1965) but also the evaporation of that sweat (Brotherhood, 2008). The latter is solely determined by environmental parameters and here the thermal elements exert their combined effects to help or hinder the efficient evaporation of sweat. This variable limit is referred to as Emax, or the evaporative capacity of the environment. Put simply, when Emax exceeds Ereq, the rate of sweat evaporation can meet Ereq, and body temperature can be controlled. Alternatively, if Ereq exceeds Emax, sweat evaporation is insufficient, heat continues to be stored, body temperature progressively rises, and EHI is a possible outcome. **Figure 7** provides an example from the Brownlow and Brotherhood study (2021), of calculated levels for Ereq and Emax on a given race day (from **Fig 6**: Venue d). For most of the race meeting, Ereq was greater than Emax and numerous cases of EHI occurred. Note the profound influence of wind speed on



Left Y aixs = rate of heat exchange for Ereq and Emax. Right Y axis = wind speed in metres per second. X axis = time of day at Venue (d).

***Fig 7:** Example of Ereq against Emax and wind speed for Venue (d). Note the profound influence of air flow on levels of Emax. Ereq = evaporative requirement = H + C + R Wm-2 (Belding & Hatch, 1955) where H = metabolic heat production; C = convective heat exchange; R = radiative heat exchange. Ereq is related to the sweat production needed to achieve cooling but this may be limited by the evaporative capacity of the environment (Emax). Emax = evaporative capacity of the environment = 11.7v 0.6 (PsaTsk-Pa) Wm-2 (Belding & Hatch, 1955); where PsaTsk = saturated vapour pressure of skin surface temperature; Pa = ambient air vapour pressure. Note that Emax is entirely a function of the environment and is profoundly influenced by air flow. Without any change to vapour pressure levels, an increase in air movement increases Emax. This means that during exercise, Emax is greatly enhanced by air movement over the skin surface, but for the stationary animal in the tie-up stalls, Emax can be severely restricted by low air movement. In circumstances such as shown in this graph, Ereq exceeds Emax. Sweat evaporation proceeds but the rate of evaporation is limited by the environmental Emax and may not be sufficient to meet Ereq, so that heat storage is unchanged and body temperature may continue to escalate, predisposing the individual to exertional heat illness (EHI).*

calculated levels of Emax at certain points in time, diminishing the risk of EHI.

For the race-day veterinarian, the theoretical constructs Ereq and Emax can be evaluated subjectively and provide valuable insight into thermoregulatory physiology. Sweating can be assessed in the immediate post-race period. Its characteristics (copious, scant, frothy, slimy, wet) and whether it evaporates rapidly and leaves a dry coat or presents as 'slimy' skin, with sweat running off dependant portions of the body onto the ground. These observations can be aligned with ambient weather conditions, providing an evaluation of sweating response (Ereq) and the efficiency of evaporative cooling (Emax).

Prevailing weather conditions do not, however, explain all cases of EHI and it can and does occur on cooler days. Some horses in this category are repeat offenders and display symptoms of EHI every time they compete. **Figure 8**, from the Brownlow and Brotherhood (2021) study, is a three-dimensional plot for the top three environmental predictors – vapour pressure (absolute humidity), wind speed and temperature. The side bar shows the percentage of horses from a race with signs of post-race EHI. Data points with a high percentage of cases are yellow, light green, green and blue-green and probably reflect environmental conditions, which are causing the EHI condition. These coloured data points are typically clustered around the known values of vapour pressure and wind speed characteristic of restricted evaporation. There are, however, numerous outliers representing only one affected horse in a single race, sometimes on a single race day. This suggests that intrinsic risk factors or extrinsic risk factors other than the weather may be causing EHI in these circumstances.

From the Brownlow and Brotherhood study (2021), mixed linear regression analyses of association between incidence of post-race EHI and environmental variables were only 43% for all weather elements and this low value agrees with the human experience amongst a variety of athletic, military and occupational settings (Budd et al., 1997; Notley et al., 2019). This residual, unexplained variation is probably attributable to the individual characteristics of the horses or to environmental factors other than the weather in the causation of EHI.

Despite the widespread use of the WBGT index, it is an imprecise indicator of environmental stress. Single values do not equate to predictable levels of clinical physiological strain (Budd, 2008) because a wide range of thermal stress can occur for a single value of WBGT. The reading does not differentiate between hot conditions and warm and humid conditions and tends to seriously underestimate the severity of high humidity, which is the cause of most cases of EHI in racehorses. It has also been suggested in the human heat illness literature that sport-context-specific research needs to be carried out so that policy guidelines can be developed on evidence-based information. One such initiative was

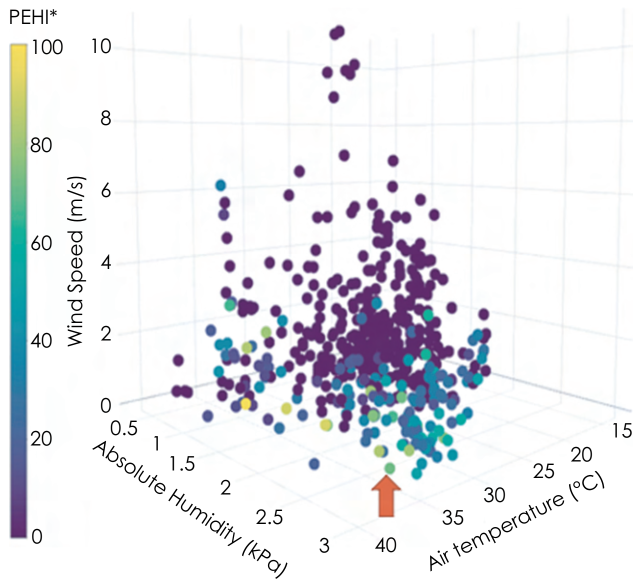


***Fig 8:** Three-dimensional density plot for the top three environmental predictors for the occurrence of exertional heat illness (EHI). Note that vapour pressure is expressed as absolute humidity (kPa). PEHI = percentage of horses showing signs of post-race EHI in a race (From Brownlow & Brotherhood, 2021). The value of this three-dimensional density plot is that it provides a unique perspective on the individual role of the three major environmental predictors for EHI. The most relevant data points are in yellow, light green and blue, representing numerous cases of post-race EHI and indicating that weather conditions are probably the major cause of the condition. Outliers in dark blue are more difficult to explain and may represent cases of EHI due to other internal risk factors. The cluster of EHI cases is approximately centred on a wind speed below 2 m/s, vapour pressure (absolute humidity) between 1.5 and 2.5 kPa, and ambient temperature between 25 and 35°C. The indicated data point represents numerous post-race EHI cases occurring at a wind speed of 0 m/s, a vapour pressure of 2.5 kPa and a temperature of 35°C.*

performed by Brownlow and Brotherhood (2021) and these authors have recommended the inclusion of vapour pressure and wind speed in conjunction with the WBGT, which would provide a more accurate assessment of risk for EHI on any given race day.

To evaluate environmental risk, it is recommended that a predictive weather site be used prior to the race day in question so that an estimation of vapour pressure, wind speed and ambient temperature can be made. For race day it is recommended that one of the hand-held weather measurement devices, such as the Kestrel Heat Stress Tracker (Kestrel Instruments) with anemometer and wind vane, be positioned in the vicinity of the tie-up stalls to monitor weather conditions in real time. This device is relatively inexpensive, easy to use and provides a WBGT reading in conjunction with ambient temperature and relative humidity, from which vapour pressure can be calculated using the recommended app. Wind speed will complete the picture. This provides the race-day veterinarian with sufficient information to know whether conditions are likely to be difficult or relatively easy in terms of management of numerous or only a few heat-affected horses.

Conclusion

Exertional heat illness is, as the name suggests, a complex illness where metabolic heat is causal and strenuous exercise is the inciting agent. There are certain misconceptions, which add confusion to understanding the illness. Firstly, it is thought that ambient weather conditions cause EHI and that it is associated mainly with extreme heat (high ambient temperatures), so that many racing jurisdictions use temperature cut-off points for cancellation of events. This means that conditions that have been shown to be most perilous for racehorses, such as mid-temperatures with high vapour pressure, may tend to be disregarded as significant heat events but will actually cause the majority of EHI cases.

Exertional heat illness is considered to be preventable, but this depends upon awareness of all aspects of the condition. Besides a knowledge of the superb thermoregulatory capacity of the racehorse, the clinical manifestations of EHI, its pathophysiology and treatment rationale, it is the thermal essentials operating on a particular race day, which demand attention and allow the most accurate prediction of risk. Intrinsic risk factors, although of vital importance, are essentially unavailable for risk assessment unless the individual animal becomes a repeat offender, which signals more intense heat mitigation strategies for that animal.

Finally, to summarise, the thermal elements act independently from each other and from metabolic heat production to alter the physical characteristics of the environment, so that on hot days they will promote heat gains and decrease the transfer of heat from the hot core to the skin surface; on humid days they combine to restrict the efficiency of evaporative cooling. In both cases, wind speed will play a critical role in the outcome. Understanding the role of the thermal elements allows a rational assessment of the risk of EHI and the requirements for supporting infrastructure, such as cooling devices and extra personnel to supervise cooling and care for horses. It is recommended that both vapour pressure and wind speed become incorporated into race-day risk-assessment protocols. Climate change experts have predicted higher levels of heat and humidity, which means that EHI could become an increasingly significant welfare issue during the next decade.

Authors' declarations of interest

No conflicts of interest have been declared.

Ethical animal research

The horse heat study formed part of the observations that are presented in this review article and was performed under the Racing NSW Animal Care and Ethics Approval Number (RNSW ARA 66).

Source of funding

Some funding was provided by Racing Australia for which the authors are most grateful.

Acknowledgements

We would like to thank the horse heat study team, who participated in taking measurements, cooling and monitoring horses as required. These were Melissa Kay, Kylie Smallwood, Pat Cozzi, Carol Griffiths, Wendy Simpson and Sue McMaster. The senior author would like to acknowledge the inspiration and direction provided by Dr John Brotherhood and Dr Grahame Budd, retired professors, renowned in the field of thermal physiology, who have been invaluable mentors for this project. The authors also wish to acknowledge some financial support from Racing Australia. Many thanks for the time and effort afforded this article by the anonymous reviewers. Open access publishing facilitated by The University of Sydney, as part of the Wiley - The University of Sydney agreement via the Council of Australian University Librarians. WOA Institution: The University of Sydney.

Authorship

M. Brownlow wrote the article. J. Mizzi collaborated in discussion, debate and experience.

References

Armstrong, L.E., Casa, D.J., Millard-Stafford, M., Moran, D.S., Pyne, S.W. et al. (2007) American College of Sports Medicine Position Stand: exertional heat illness during training and competition. *Medicine & Science in Sports & Exercise*, **39**, 556–572.

Belding, H.S. & Hatch, T.V. (1955) Index for evaluating heat stress in terms of the resulting physiological strains. *Heating, Piping, and Air Conditioning*, **27**, 129–136.

Brocherie, F., Girard, O., Pezzoli, A. & Miller, G.P. (2014) Outdoor exercise performance in ambient heat: Time to overcome challenging factors? *International Journal of Hyperthermia*, **30**, 547–549.

Brocherie, F. & Milet, G.P. (2015) Is the WBGT index relevant for exercise in the heat? *Sports Medicine*, **45**, 1619–1621.

Brotherhood, J.R. (2008) Heat stress and strain in exercise and sport. *Journal of Science and Medicine in Sport*, **11**, 6–19.

Brownlow, M.A. & Brotherhood, J. (2021) An investigation into environmental variables influencing the incidence of exertional heat illness in Thoroughbred racehorses in temperate eastern Australia. *Australian Veterinary Journal*, **99**, 433–481.

Brownlow, M.A. & Mizzi, J.X. (2022a) Thermoregulatory capacity of the Thoroughbred racehorse and its relationship to the pathogenesis of exertional heat illness. *Equine Veterinary Education*, **34**, 214–221.

Brownlow, M.A. & Mizzi, J.X. (2022b) Exertional heat illness in Thoroughbred racehorses – Pathophysiology, case definition and treatment rationale. *Equine Veterinary Education*, **34**, 259–271.

Brownlow, M.A. & Smith, T. (2020) The use of the hand-held infrared thermometer as an early detection tool for exertional heat illness in Thoroughbred racehorses: a study at racetracks in eastern Australia. *Equine Veterinary Education*, **33**, 296–305.

Budd, G.M. (2001) Assessment of thermal stress – the essentials. *Journal of Thermal Biology*, **26**, 371–374.

Budd, G.M. (2008) Wet-bulb globe temperature (WBGT) – its history and limitations. *Journal of Science and Medicine in Sport*, **11**, 20–32.

Budd, G.M., Brotherhood, J.R., Hendrie, A.L., Jeffery, S.E., Beasley, F.A., Costin, B.P. et al. (1997) Project Aquarius 9. Relative influence of job demands and personal factors on the energy expenditure, strain, and productivity of men suppressing wildland fires. *International Journal of Wildland Fire*, **7**, 159–166.

Butler, P.J., Woakes, A.J. & Smale, K. (1993) Respiratory and cardiovascular adjustments during exercise of increasing intensity and during recovery in thoroughbred racehorses. *Journal of Experimental Biology*, **179**, 159–180.

Casa, D.J., Hosokawa, T.Y., Belval, L.N., Adams, W.M. & Stearns, R.L. (2017) Preventing death from exertional heat stroke – the long road from evidence to policy. *Kinesiology Review*, **6**, 99–109.

D'Ambrosio Alfano, F.R., Malchire, J., Palella, B.I. & Riccio, G. (2014) WBGT index revisited after 60 years of use. *Annals of Occupational Hygiene*, **58**, 995–970.

Davies, C.T.M. (1979) Influence of skin temperature on sweating and aerobic performance during severe work. *Journal of Applied Physiology*, **56**, 686–692.

Davis, R.E., McGregor, G.R. & Enfield, K.B. (2016) Humidity. A review and primer of atmospheric moisture and human health. *Environmental Research*, **144**, 106–116.

Geor, R.J., McCutcheon, L.J., Ecker, G.L. & Lindinger, M.I. (2000) Heat storage in horses during submaximal exercise before and after humid heat acclimation. *Journal of Applied Physiology*, **89**, 2283–2293.

Guthrie, A.J. & Lund, R.J. (1998) Thermoregulation: base mechanisms and hyperthermia. *Veterinary Clinics of North America: Equine Practice*, **14**, 45–59.

Hodgson, D.R., McCutcheon, L.J., Byrd, S.K., Brown, W.S., Bayley, W.M., Brengelmann, G.L. et al. (1993) Dissipation of metabolic heat in the horse during exercise. *Journal of Applied Physiology*, **74**, 1161–1170.

Hodgson, D.R., Rose, R.J., Kelso, T.B., McCutcheon, L.J., Bayly, W.M. & Gollnic, P.D. (1990) Respiratory and metabolic responses in the horse to moderate and heavy exercise. *Pflugers Archiv. European Journal of Physiology*, **417**, 73–78.

Jay, O. & Brotherhood, J.R. (2016) Occupational heat stress in Australian workplaces. *Temperature*, **3**, 394–411.

Jeffcott, L.B. & Kohn, C.W. (1999) Contributions to equine exercise physiology research to the success of the 1996 Equestrian Olympic Games: a review. *Equine Veterinary Journal*, **31**, 347–355.

Jeffcott, L., Leung, W. & Riggs, C. (2009) Managing the effects of weather on the equestrian events of the 2009 Beijing Olympic Games. *The Veterinary Journal*, **182**, 412–429.

Jessen, C. (Ed.) (2000) Pathophysiology of temperature regulation: hyperthermia and heat stroke. In: *Temperature regulation in humans and other mammals*. New York: Springer-Verlag, pp. 161–164.

Blazejczyk, K., Tokura, H., Bortkiewicz, A. & Szymczak, W. (1999) Solar radiation and thermal physiology in man. In: De Dear, R.J., Kalma, J.D., Oke, T.R. & Auliciems, A. (Eds.) *Biometeorology and urban climatology at the turn of the millennium*, Conference ICB-ICUC'99, (Sydney, 8-12 Nov 1999). Geneva: WMO, pp. 267–271.

MacDonald, D.M., Wheeler, D.O., Guthrie, A.J., Kok, C. & Pilgrim, T. (2008) "Post race distress syndrome" in thoroughbred racing in South Africa. Proceedings of the International Conference of Racing Analysts and Veterinarians.

McConaghy, F.F., Hodgson, D.R., Evans, D.L. & Rose, R.J. (1995) Effects of two types of training on sweat composition. *Equine Veterinary Journal*, **27**, 285–288.

McCutcheon, L.J. & Geor, R.J. (1998) Sweating: fluid and ion losses and replacement. *Veterinary Clinics of North America: Equine Practice* **14**, 75–95.

McCutcheon, L.J. & Geor, R.J. (2008) Thermoregulation and exercise-associated heat stress. In: Hinchcliff, K., Kaneps, A. & Geor, R. (Eds.) *Equine exercise physiology*. Philadelphia, US: Elsevier Health Sciences, pp. 382–395.

McNicholl, J., Howarth, G.S. & Hazel, S.J. (2016) Influence of the environment on body temperature of racing Greyhounds. *Frontiers in Veterinary Science*, **3**, 1–12.

Nielsen, B. & Nielsen, M. (1965) On the regulation of sweat secretion in exercise. *Acta Physiologica Scandinavica*, **64**, 314–322.

Nomura, M., Shiose, T., Ishikawa, Y., Mizobe, F., Saki, S. & Kusano, K. (2019) Prevalence of post-race exertional heat illness in Thoroughbred racehorses and climate conditions at racecourses in Japan. *Journal of Equine Science*, **30**, 17–23.

Notley, S.R., Lamarche, D.T., Meade, R.D., Flouris, A.D. & Kenny, G.P. (2019) Revisiting the influence of individual factors on heat exchange during exercise in dry heat using direct calorimetry. *Experimental Physiology*, **104**, 1038–1050.

Otani, H., Goto, T., Goto, H. & Shirato, M. (2017) Time-of-day effects exposure to solar radiation on thermoregulation during outdoor exercise in the heat. *Chronobiology International*, **34**, 1224–1238.

Otani, H., Goto, T., Goto, H., Hosokawa, Y. & Shirato, M. (2019) Solar radiation exposure has diurnal effects on thermoregulatory responses during high intensity exercise in the heat outdoors. *The Journal of Strength and Conditioning Research*, **33**, 2608–2615.

Otani, H., Kaya, M., Tamaki, A., Watson, P. & Maughan, R.J. (2016) Effects of solar radiation on endurance exercise capacity in a hot environment. *European Journal of Applied Physiology*, **116**, 769–779.

Otani, H., Kaya, M., Tamaki, A., Watson, P. & Maughan, R.J. (2018) Air velocity influences thermoregulation and endurance exercise capacity in the heat. *Applied Physiology, Nutrition, and Metabolism*, **43**, 131–138.

Otani, H., Kaya, M., Tamaki, A., Goto, H., Tokizawa, K. & Maughan, R.J. (2021) Combined effects of solar radiation and airflow on endurance exercise capacity in the heat. *Physiology & Behavior*, **229**, 113264.

Parsons, K. (2002) *Human thermal environments. The effects of hot, moderate and cold environments on human health, comfort and performance*, 3rd edn. CRC Press, Taylor and Francis Group LLC.

Parsons, K. (2006) Heat stress standard ISO 7243 and its global application. *Industrial Health*, **44**, 368–379.

Periard, J.D., Jay, O., Alonso, J.M. & Coutts, A.J. (2015) Author's reply to Brocherie and Millet: 'Is the wet bulb globe temperature (WBGT) index relevant for exercise in the heat?'. *Sports Medicine*, **45**, 1623–1624.

Racinais, S., Akonso, J.M., Coutts, A.J., Flouris, A.D., Girard, O., González-Alonso, J. et al. (2015) Consensus recommendations on training and competing in the heat. *Sports Medicine*, **45**, 925–938.

Saunders, A.G., Dugas, J.P., Tucker, R., Lambert, M.I. & Noakes, T.D. (2005) The effects of different air velocities on heat storage and body temperature in humans cycling in a hot, humid environment. *Acta Physiologica Scandinavica*, **183**, 241–255.

Sawka, M.N. & Young, A.J. (2006) Physiological systems and their responses to conditions of heat and cold. In: Tipton, C.M., Sawka, M.N., Tate, C.A. & Terjung, R.L. (Eds.) *ACSM'S advanced exercise physiology*, Baltimore: Lippincott, Williams and Wilkins, **26**, 535–563.

Schroter, R.C., Marlin, D.J. & Jeffcott, L.B. (1996) Use of the wet-bulb globe temperature (WBGT) to quantify environmental heat loads during three-day event competitions. *Equine Veterinary Journal*, **28**, 3–6.

Walsberg, G.E., Campbell, G.S. & King, J.R. (1978) Animal coat colour and radiative heat gain: a re-evaluation. *Journal of Comparative Physiology*, **126**, 211–222.

Weishaupt, M.A., Staempfli, H. & Belleter, R. (1996) Temperature changes during strenuous exercise in different body compartments of the horse. *Pferdeheilkunde*, **12**, 450–454.

Westwood, C.S., Fallowfield, J.L., Delves, S.K., Nunns, M., Ogden, H.B. & Layden, J.D. (2020) Individual risk factors associated with exertional heat illness: a systemic review. *Experimental Physiology*, **106**, 191–199.

Yaglou, C.P. & Minard, D. (1957) Control of heat casualties in military training centers. *A.M.A. Archives of Industrial Health*, **16**, 302–316.