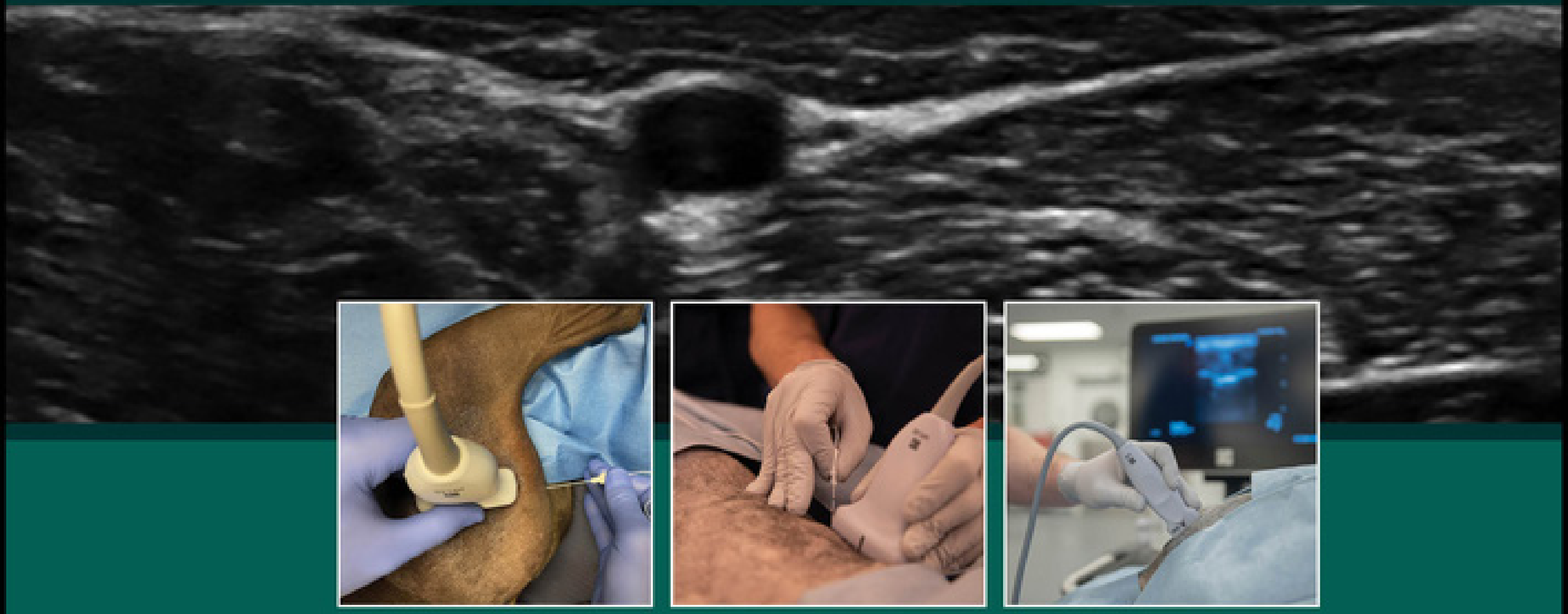
Second Edition

Small Animal Regional Anesthesia and Analgesia

Edited by

Matt Read • Luis Campoy • Berit Fischer



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Small Animal Regional Anesthesia and Analgesia

Dedication

I would first like to thank my family for their support and patience while I have worked on this project over the last few years. Emma, thank you for being our family's rock, for inspiring me to be the best version of myself every day, and for challenging me to think of new ways to do things. Grace and Kate, thank you for putting up with the endless hours "on my computer" at the airport and at your horse shows. I am so proud to be your dad and have loved every minute of watching you pursue your passions and succeed in ways we could have never imagined a few short years ago! Our family means everything to me, and I am so thankful to have all of you in my life. Love you guys!

I'd also like to recognize the patients that I get to work with every day. I learn so much from getting to practice anesthesia as part of your medical care and have grown so much as a veterinarian since I have started to see what lies inside and can be better at my job on your behalf.

Finally, I'd like to thank Luis and Berit for years and years of wonderful friendship and their tireless efforts in getting this edition of our book across the finish line. I can't wait to start working on the third edition with you!

Matt Read

At the time of writing this, it feels like we have written and edited a book and a half! It has been a difficult time, filled with unprecedented challenges, and yet, here we are, we made it! During this time, there were many times in which this project was still a big question mark. This is when my partner in crime comes in. Always with encouragement and amazing management skills! Matt Read has guided me through this process all the way to the end! Thank you auld friend!

To Berit Fischer, our new addition to the team and dear friend for many years … since her Ithaca times! We go back a while, I know … What a journey! This one will be difficult to forget!

To all the authors in this book and those that were authors and then weren't anymore … This project went through many stages and many designs … as I said … unprecedented times and challenges in making this book a reality. This book is also yours!

To all my workmates, especially Drs. Manuel Martin-Flores, Robin Gleed, and Jordyn Boesch, for allowing me to go into close confinement to "type and read stuff"!

Finally, to my beloved wife and children, Ewa, Kyla, and Kian, for being so patient with me and never asking why…

Luis Campoy

To my mom, my editor growing up in more ways than one, who taught me to always pay attention to the details. To my dad, my running partner, who never let me quit. To my husband, Mike, who smiled and said "Go for it" when I was presented with the opportunity to be an editor for this book. His support throughout my career has been steadfast and in ways I can never repay. To my two amazing daughters, Abigail and Ilse, who continue to inspire me daily with their creativity and thirst for knowledge. I am so incredibly fortunate. And to my co-editors and friends, Matt and Luis, who, having both been mentors at different points in my career, decided to share this journey with me. Until next time…

Berit Fischer

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SECOND EDITION

Edited by

Matt Read
Anesthesiologist and Specialty Team Leader
MedVet, Worthington, OH, USA

Luis Campoy
Clinical Professor of Anesthesiology and Pain Medicine
Section Chief of Anesthesiology and Pain Medicine
College of Veterinary Medicine
Cornell University
Ithaca, NY, USA

Berit Fischer
Head of Anesthesia and Pain Management
Eastern Pennsylvania Veterinary Medical Center
Allentown, PA, USA

WILEY Blackwell

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List of Contributors

Chiara Adami
Department of Veterinary Medicine
University of Cambridge
Cambridge
United Kingdom

Eric D. Brumberger
Weill Cornell Medicine, Department of Anesthesiology
NewYork-Presbyterian Hospital
New York, NY
USA

Luis Campoy
College of Veterinary Medicine
Cornell University
Ithaca, NY
USA

Tatiana H. Ferreira
School of Veterinary Medicine
University of Wisconsin, Madison
Madison, WI
USA

Berit L. Fischer
Eastern Pennsylvania Veterinary Medical Center
Allentown, PA
USA

Marta Garbin
Department of Clinical Sciences, Faculty of Veterinary Medicine
Université de Montréal
Saint-Hyacinthe, QC
Canada

Augusto Matias Lorenzutti
Facultad de Ciencias Agropecuarias
IRNASUS CONICET-Universidad Católica de Córdoba
Córdoba
Argentina

Stephan Mahler
Bestin'Vet
Saint Grégoire
France

Manuel Martin-Flores
Department of Clinical Sciences, College of Veterinary Medicine
Cornell University
Ithaca, NY
USA

Micheál Ó Cathasaigh
MOC Veterinary Radiology Ltd.
St. Neots, Cambridgeshire
UK

Pablo E. Otero
Division of Anaesthesiology and Pain Management
College of Veterinary Medicine
Buenos Aires University
Ciudad Autónoma de Buenos Aires
Argentina

Peter Pascoe
Department of Surgical and Radiological Sciences
University of California
Davis, CA
USA

Diego A. Portela
Department of Comparative, Diagnostic and Population Medicine
College of Veterinary Medicine
University of Florida
Gainesville, FL
USA

Matt Read
MedVet
Worthington, OH
USA

Marta Romano
Department of Comparative, Diagnostic and Population Medicine
College of Veterinary Medicine
University of Florida
Gainesville, FL
USA

Yael Shilo-Benjamini
Koret School of Veterinary Medicine
The Hebrew University of Jerusalem
Rehovot
Israel

Alexander C. S. Thomson
CityU Veterinary Medical Centre
Sham Shui Po, Kowloon
Hong Kong

Jaime Viscasillas
Anaesthesia Service and Pain Clinic
Silla, Valencia
Spain

Foreword

For many years, the use of local anesthetics in general veterinary practice was largely confined to providing surgical anesthesia for ruminants and performing diagnostic nerve blocks in horses. The first edition of Small Animal Regional Anesthesia and Analgesia, published in 2013, was a driving force behind the widespread adoption of locoregional anesthesia by companion animal practitioners. Since that edition of the book, the practice of locoregional anesthesia has progressed substantially, and this eagerly awaited second edition is an up-to-date reference and learning guide for the small animal practitioner.

Local anesthetic techniques are now used routinely in surgical practice to provide intra- and postoperative analgesia. These techniques allow major surgery to be accomplished at minimal depths of anesthesia and even with procedural sedation. When longer-acting local anesthetics are used, good-quality pain relief can persist well into the postoperative period. Systemic analgesics, such as opioids and nonsteroidal anti-inflammatory drugs (NSAIDs), are beset with adverse side effects and regulatory impediments to their use. The need for opioids and NSAIDs in veterinary practice will be reduced with increasing use of locoregional anesthesia. Some of the procedures described here are of interest to practitioners for relief of chronic pain, e.g., palliative care of patients with limb osteosarcoma.

The chapters are named for the nerves that are to be blocked – and each starts with a section (Block at a Glance) that summarizes the technique and its probable uses. The images include high-quality photographs, dissections, and ultrasonographs that are essential complements to the text. The quality of a nerve block is related directly to the precision with which a local anesthetic is injected. Echolocation is the most precise method available to clinicians for depositing local anesthetic proximate to target nerves – it is superior even to electrolocation. In general, such ultrasound-guided blocks performed by educated operators produce better-quality analgesia than alternative techniques and generate fewer adverse side effects. Fortunately, high-definition ultrasound equipment is now available to the general practitioner, and the editors of this book describe the approach to each block using echolocation.

As was its predecessor, this edition will surely become a primary resource for veterinary students, technicians, general practitioners, surgeons, anesthesiologists, and pain practitioners.

Robin D. Gleed, BVSc, MA, MRCVS, DVA,
DACVAA, DipECVAA, MRCA

Professor of Anesthesiology and Pain
Management

Senior Associate Chair,
Department of Clinical Sciences
Cornell University

Preface

2023 marked the ten-year anniversary of the first edition of *Small Animal Regional Anesthesia and Analgesia*, aka "The Green Book", whose success over the last decade was based on the nature of its novel content and practicality. Publication of that book changed our professional lives as well as the lives of many veterinarians and veterinary team members who had an interest in anesthesia and pain management. We are so appreciative of the amazing group of contributors who helped bring that book to fruition and shared their expertise and enthusiasm for this growing area of anesthesia with our readers. We have heard time and again how the information in that edition contributed to the improved comfort and well-being of many pets worldwide and are still somewhat shocked that our book could have made such an impact.

When the first edition of *Small Animal Regional Anesthesia and Analgesia* was published, veterinary locoregional anesthesia was still considered by many to be more "art" than "science" and something that was practiced by few. Over the past ten years, interest in and knowledge of small animal locoregional anesthesia have grown exponentially beyond the scope of the first edition. Blocks have now reached into parts of the body that many of us had never envisioned (or even heard of!) and the field is maturing as a subspecialty thanks to the tireless efforts, thoughtful research, and reporting of clinical experiences of many, many people from around the world. Dissemination of new information pertaining to this exciting area of small animal anesthesia continues to rise through publications, instruction, and casual conversations, and our collective knowledge continues to grow every year for the betterment of the patients we serve.

This new, second edition of *Small Animal Regional Anesthesia and Analgesia* represents a significant revision of our original book, and we are very excited to share it with you. Following a similar path to the one taken by many of our physician counterparts, we have chosen to focus this edition almost exclusively on the use of ultrasound-guided techniques since that is the direction the published literature and clinical practice are taking us. Although we will undoubtedly miss including something, we have tried to be as all-encompassing as we could in terms of summarizing what has been published to date and including as much as is currently known about the anesthetic and analgesic techniques that the use of ultrasound affords us. We have also restructured the presentation of the content to follow a relatively consistent template, making it easier for you, the reader, to find the specific information you might be looking for. We have also tried to include the types of images that will enhance your learning and understanding of the information that is presented in the text, allowing you to appreciate many of the subtle aspects that still fall under the category of "art." This mammoth endeavor led us to add another editor to the project and to invite a dozen new and distinguished colleagues from around the world to share their varied expertise and experiences with us. Together, they have made our vision for the new edition a reality, and we are so very grateful for their support of this project and their continued friendships.

We originally set out on this project with the same goals that we outlined in the first edition of *Small Animal Regional Anesthesia and Analgesia*: to summarize the peer-reviewed and evidence-based literature for our readers, to standardize the techniques and associated nomenclature that are described, to further stimulate interest in this exciting area of veterinary anesthesia, and to improve patient care by creating a resource that would be accessible and helpful to everyone, regardless of their level of experience or training. Although we are confident that this book will be of use to students, veterinarians, technicians, veterinary anesthesiologists, and other veterinary specialists who are interested in improving their understanding of how local and regional anesthesia might fit into their practices, we appreciate that there is still so much for all of us to learn. We hope that we have achieved these goals and that you enjoy and benefit from the information in this book as much as we and our colleagues have enjoyed and benefited from preparing it.

Leave no patient unblocked! But first, do no harm... Let us continue on this journey together.

Matt, Luis, and Berit

January 2024

Acknowledgments

We would first like to acknowledge our amazing collaborators and coauthors, all of whom had great enthusiasm for seeing this new edition of Small Animal Regional Anesthesia and Analgesia come to fruition. So much has been learned and developed since the first edition was published, and it took a village to distill everything that is currently known into a single resource. Thank you all for your time, energy, and passion for sharing what you know with the world!

We also want to thank the exceptional team at Wiley for their support and patience. After many delays, we are all very thankful to see this project finally completed! We would especially like to extend our thanks to Ms. Erica Judisch, Executive Editor, Veterinary Medicine and Dentistry, for her friendship, tireless patience, and understanding over the last ten years. Without her, this edition would never have happened. We are also very grateful for Ms. Vallikkannu Narayanan, Managing Editor, Health Professions and Veterinary Medicine; Ms. Merryl Le Roux, our previous Managing Editor, Health and Life Sciences; and Ms. Susan Engelken, Editorial Publication Coordinator and all that they contributed to the process.

Considerations for Locoregional Anesthesia

PART 1

Ultrasound Guidance

The Inevitable Evolution of Locoregional Anesthesia

CHAPTER 1

Berit L. Fischer

> There's a way to do it better. Find it.
>
> —Thomas Edison

INTRODUCTION

It should come as no surprise that advancements in veterinary medicine often follow those in human medicine, and it is no different with the evolution and use of locoregional anesthesia. This is despite the fact that animals are often used to study and develop new techniques before they are ever used in people. Even Carl Koller, the Austrian ophthalmologist who first used topical cocaine to induce sensory anesthesia of the cornea in a patient for glaucoma surgery in 1884, first experimented with its desensitizing effects on the corneas of dogs and guinea pigs (Calatayud and González 2003).

The interest in, and use of, locoregional techniques has increased significantly. Much of the research up until the mid-1990s focused on the discovery of new drugs (e.g. bupivacaine, ropivacaine, bupivacaine liposome injectable suspension), techniques (e.g. nerve block catheters), and adjuvants (e.g. dexamethasone, clonidine, etc.) that could be used to extend the duration of anesthesia and analgesia provided to patients (Dahl et al. 1988; Eledjam et al. 1991; McGlade et al. 1998). Additionally, methods to assist in nerve location (i.e. paresthesia, electrical nerve stimulation) were sought to provide ways other than anatomic landmarks to target peripheral nerves, and hopefully, improve patient safety and increase success. In 1994, this search culminated in the use of ultrasound guidance when Kapral et al. (1994) published a randomized, controlled trial examining ultrasound-guided brachial plexus blocks in people. A new era in locoregional anesthesia had begun.

ULTRASOUND TECHNOLOGY

A BRIEF HISTORY

The discovery of piezoelectricity by brothers, Jacque and Pierre Curie in 1880, provided the foundation for the development of the modern-day ultrasound transducer. By applying an electric current to quartz crystals, they caused the crystals to vibrate and produce ultrasonic waves. This revolutionary finding became critical to the development of sonar that was used by submarines in World War I, and of ultrasound therapy whereby physicians could use the vibrations that were produced to treat a variety of illnesses (Duck 2021). It was not until 38 years later, in 1928, that Russian physicist SY Sokolov utilized ultrasound for imaging purposes. He invented an ultrasound transducer using a single transmitter and receiver that, when placed on opposite sides of a metal sheet, was able to detect imperfections in the metal and display line images produced from the disruptions in sound wave transmission (Duck 2021).

Ultrasound for medical imaging eventually emerged after several researchers struggled to develop transducers that could work in a hospital setting. In 1956, a predecessor of today's B-mode (i.e. "brightness" mode) ultrasound, the 2-D compound scanner, was developed by obstetrician Ian Donald and engineer Tom Brown to image an unborn fetus (Whittingham 2021) (Figure 1.1). Worldwide advancement of ultrasound technology continued throughout the 1960s and 1970s, culminating in the invention of the linear array transducer that utilized several rows of transducer elements to produce real-time scanning (Whittingham 2021).

USE OF ULTRASOUND FOR LOCOREGIONAL ANESTHESIA

Using ultrasound technology to assist with performing locoregional blockade was first reported by la Grange et al. (1978) who, after identifying the subclavian artery using Doppler ultrasound, performed supraclavicular brachial plexus blocks in 61 patients using anatomy and the presence of paresthesia to determine where to deposit the local anesthetic. It was not until 1994, however, that the use of ultrasound was first described to help guide a stimulating needle toward the target nerve trunks when performing brachial plexus blocks via both axillary and supraclavicular approaches (Kapral et al. 1994).

ULTRASOUND-GUIDED LOCOREGIONAL ANESTHESIA IN VETERINARY SPECIES

As the use of ultrasound guidance in regional anesthesia grew in human medicine, its use slowly started to emerge in the veterinary literature, first with a paper describing the sonographic appearance of canine sciatic nerves in 2007, followed

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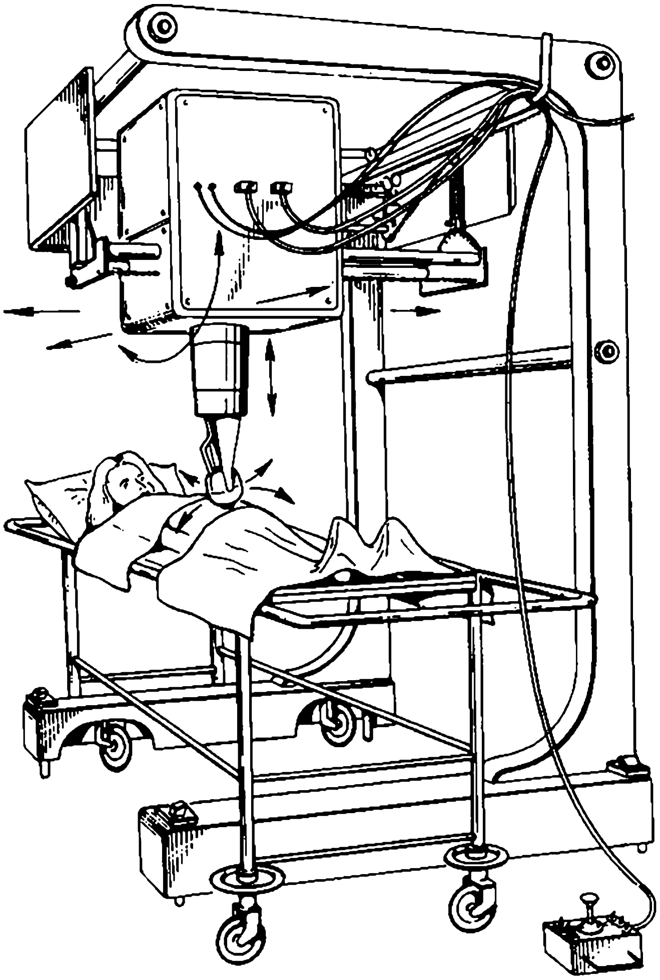

FIGURE 1.1 Drawing of the 2-D compound scanner, developed through the collaborative efforts of Dr. Ian Donald and Tom Brown. Source: McNay and Fleming (1999)/with permission of Elsevier.

shortly thereafter by a similar study that described the use of ultrasound for evaluation of the canine brachial plexus (Benigni et al. 2007; Guilherme and Benigni 2008).

The first study to describe the use of ultrasound-guided blocks in dogs was accepted for publication in 2009 (Campoy et al. 2010). That study reported using an in-plane needle technique to approach the brachial plexus and the femoral and sciatic nerves in medium- and large-breed dogs. Each approach was followed by deposition of a mixture of lidocaine and methylene blue at the target site, allowing for later identification of nerve staining after euthanasia of the dogs for unrelated purposes. Later that same year, the first efficacy study that documented successful sensory blockade following ultrasound-guided saphenous and sciatic nerve blocks in dogs was submitted for publication by Costa-Farré et al. (2011), and the first description of using ultrasound-guided blocks in cats was published by Haro et al. in 2013. Since then, use of ultrasound guidance for nerve blocks has been reported in a wide range of veterinary species (De Vlamynck et al. 2013; Hughey et al. 2022).

HOW ULTRASOUND GUIDANCE HAS CHANGED LOCOEGIONAL ANESTHESIA

Objective measurement of the impact a new modality or treatment has on an industry, in this case medicine, can be difficult to determine, particularly when it is first being instituted. Fortunately, the impact of ultrasound guidance on regional anesthesia has been established. In 2017, Vlassakov and Kissin (2017) published a study assessing notable advances in regional anesthesia from 1996 through 2015. They evaluated meta-analyses that had been published on a variety of regional anesthesia topics based on their ability to demonstrate measurable clinical benefits. Various topics were analyzed based on their level of academic interest, findings of statistically significant effects, their overall risk of bias, the degree of heterogeneity between the studies within each meta-analysis, and the determination of a minimal clinically important difference (MCID). Of all the topics they analyzed, they concluded that within this 20-year time period, the discovery and development of ultrasound guidance for performing upper and lower limb peripheral nerve blocks was the one of greatest clinical importance.

This has been supported in practice by several studies that compared the use of ultrasound guidance to other methods of nerve location (i.e. electrostimulation, paresthesia, etc.) for performing regional blocks. A compilation of these findings, published by the American Society of Regional Anesthesia and Pain Medicine (ASRA), provided an objective evidence-based assessment of the literature in order to determine if ultrasound guidance produced a positive effect on the performance, efficacy, and/or safety of regional blocks over other methods of nerve location (Neal et al. 2016). As interest has grown, the feasibility of incorporating ultrasound guidance into large-scale operations and its financial impact have also been investigated and addressed through cost-analysis studies (Liu and John 2010; Ehlers et al. 2012).

PERFORMANCE AND EFFICACY

The ASRA determined that when ultrasound guidance was compared to other methods of nerve location for extremity blocks, it was favored based on fewer needle passes, faster block performance, decreased onset time, and greater block success, with high levels of evidence and minimal differences between upper and lower extremities (Neal et al. 2016). Use of ultrasound guidance for neuraxial blocks also demonstrated superior performance when compared to palpation in terms of determining the correct vertebral interface, requiring fewer needle sticks, and the ability to accurately predict the needle insertion depth to the target ahead of time. Less demonstrable evidence was available at the time of that study to fully evaluate the impact of ultrasound guidance on the performance of truncal blocks, with many of the techniques currently being used still in development and/or lacking methods of comparison to other techniques.

SAFETY

When compared to other methods, one of the most notable benefits of incorporating ultrasound guidance into performance of regional anesthesia is a decreased incidence of local anesthetic systemic toxicity (LAST). Barrington and Kluger (2013) published a landmark study that evaluated the incidence of LAST following peripheral nerve blockade using either ultrasound-guided or non-ultrasound-guided techniques in 20021 patients (25336 blocks). They determined that use of ultrasound guidance reduced the risk of LAST by more than 65% compared to when other techniques were used. This was likely due to being able to visualize and avoid large blood vessels in the target area, recognizing potential intravascular injections earlier by noting the absence of local anesthetic spread in the area of interest, being able to use smaller local anesthetic doses to achieve successful blockade, and requiring fewer repeat blocks because of block failure (Marhofer et al. 1998; Barrington and Kluger 2013). Of particular interest, though not reported in other studies, was that there was no difference in the incidence of vascular puncture between the different groups. Barrington and Kluger postulated that when vascular punctures occurred during performance of ultrasound-guided blocks, they did not result in LAST because the intravascular injections were recognized by the anesthetist and halted before their patients developed clinical signs. With development of newer technologies, such as color power Doppler, the ability to identify smaller, low-flow blood vessels near the area of interest may be further improved, preventing vascular punctures, and accentuating the benefits of ultrasound- over non-ultrasound-guided techniques for preventing LAST to a greater extent (Martinoli et al. 1998).

While several areas within regional anesthesia have been impacted positively by the introduction of ultrasound guidance, the ASRA was unable to find an appreciable difference in the incidence of neurologic complications (i.e. sensorimotor deficits) following peripheral nerve blockade when ultrasound was used versus not (Neal et al. 2016). Several explanations were provided, including lack of technical skill or training of the anesthetist, the inability of ultrasound technology to provide the necessary resolution to allow discrimination between neural and nonneural tissues, and the presence of anatomical barriers that impair visualization of the needle tip.

A retrospective analysis comparing the incidence of neurologic outcomes following interscalene brachial plexus blocks in people before and after the institution of ultrasound guidance was published the same year as the ASRA assessment (Rajpal et al. 2016). Those authors found that the incidence of neurologic complications was significantly lower with ultrasound guidance than the historical rates that were published for the same block using electrostimulation (2% versus 10%, respectively). These results could indicate that ultrasound guidance, when specific blocks are evaluated (particularly those with higher risk of nerve injury), may demonstrate a better risk profile for postoperative neurologic symptoms versus evaluating all blocks as a whole. The potential benefit of using ultrasound to reduce the incidence of neurologic injury has not been definitively proven, so anesthetists need to demonstrate continued diligence when performing blocks, even if ultrasound is being used.

FINANCIAL IMPACT

Incorporation of new modalities is often associated with a price tag. Cost, in many situations, may determine whether a new technique has the ability to be utilized by a larger medical population. Studies in people have investigated the financial impact of using ultrasound guidance for performing locoregional blocks versus other methods. A study that used computer modeling to evaluate cost differences between ultrasound-guided and nerve stimulation for regional anesthesia determined that, when used in an ambulatory setting, ultrasound-guided blocks only became more expensive than using nerve stimulation if the block success rate for nerve stimulation was >96% (Liu and John 2010). This is considerably higher than success rate outcomes for several randomized controlled studies where complete sensory block using nerve stimulation occurred 27–76% versus 87–100% of the time when using ultrasound guidance (Liu 2016).

A prospective clinical study evaluating the cost-effectiveness of ultrasound-guided versus nerve stimulator-guided catheter insertion for continuous sciatic nerve blocks had similar, albeit more relevant, findings (Ehlers et al. 2012). Those authors used the ratio of added cost to the number of additional successful nerve blocks to determine that the use of ultrasound guidance is 84.7% more likely to be effective and less expensive than use of nerve stimulation. It is important to remember, however, that these numbers have the ability to be influenced by several factors, including fluctuating costs of equipment, caseload, and expertise of personnel.

VETERINARY MEDICINE

PERFORMANCE, EFFICACY, AND SAFETY

Only two studies have evaluated the use of ultrasound guidance versus other methods of nerve location in veterinary species, likely a reflection of the relative newness of these techniques and the number of individuals performing them. Both studies compared ultrasound guidance to nerve stimulation in dogs undergoing brachial plexus blocks. Using six Beagles in a crossover study, Akasaka and Shimizu (2017) found that the use of ultrasound guidance resulted in faster block performance, faster onset time, and longer duration of analgesia than when nerve stimulation was used with similar efficacy. Another small clinical study ($n = 32$) sought to determine the differences in complication rates and efficacy in dogs undergoing either ultrasound-guided or nerve-stimulator-guided brachial plexus blocks for thoracic limb surgery. Block success rate in this study was 87% (14/16 dogs) for ultrasound-guided blocks and 75% (12/16 dogs) for nerve stimulator-guided blocks ($P > 0.05$), with similar rates of minor complications (i.e. hypotension, Horner's syndrome) in both groups (Benigni et al. 2019). Unfortunately, these studies do not allow specific metrics or meta-analyses to be performed, leaving veterinary clinicians to rely upon those recommendations produced from studies in people until more data becomes available.

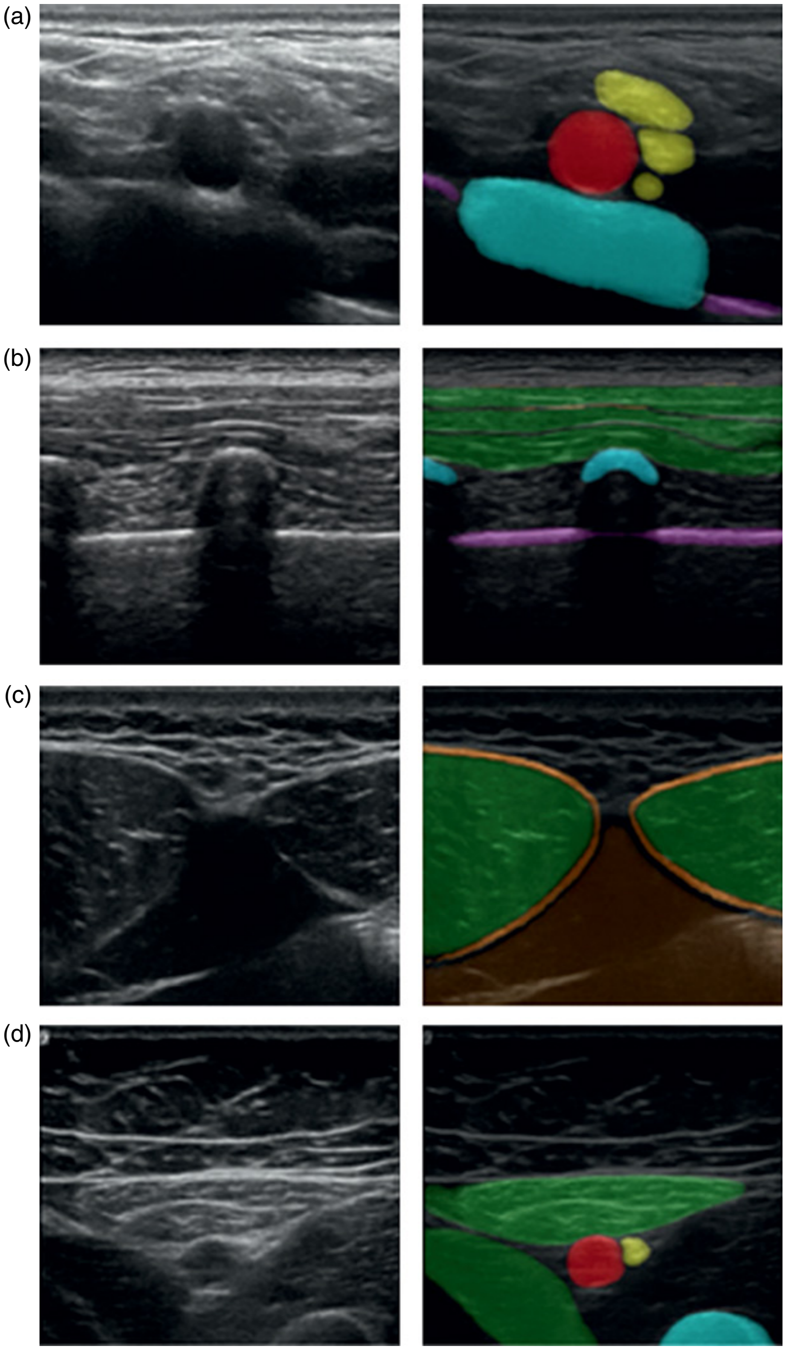

FIGURE 1.2 Ultrasound images of (a) brachial plexus (supraclavicular level); (b) erector spinae plane; (c) rectus sheath; and (d) adductor canal (mid-thigh). Images on the right have artificial intelligence (AI)-assisted identification (ScanNav™ Anatomy PNB) of bone (blue), blood vessels (red), nerves (yellow), fasciae (orange), pleura (purple), and peritoneum (brown). Source: From Bowness et al. (2021)/John Wiley & Sons.

FINANCIAL IMPACT

A recent study by Warrit et al. (2019) compared the financial impact of using ultrasound-guided lumbar plexus and sciatic nerve blocks that were confirmed with nerve stimulation versus no blocks in dogs undergoing tibial plateau leveling osteotomies. Those authors found that dogs that did not receive peripheral nerve blocks had more episodes of hypotension, more interventions to manage hypotension, and more requirements for postoperative rescue analgesia both immediately upon recovery, as well as over the next 12 hours, than dogs that received ultrasound-guided blocks. As a result, dogs in the no-block group had significantly greater and more variable anesthesia costs than the dogs receiving nerve blocks, despite the increased cost of using more advanced equipment such as the ultrasound machine. The authors acknowledged that these cost savings could vary or even be negated in patients that did not develop hypotension or other complications requiring additional interventions. It is worth mentioning that fixed anesthesia costs were not significantly different, with no difference in total anesthesia time being observed between the two groups ($P = 0.4$). This may speak to the use of ultrasound guidance and its ability to decrease the time it takes to perform peripheral nerve blocks, similar to what has been shown in people.

WHAT IS NEXT?

Many of the challenges of performing ultrasound-guided regional anesthesia have primarily been attributed to lack of anesthetist skill and training or technological limitations of currently available ultrasound equipment. These include the inability to identify the needle tip due to anatomic impediments, steep angles or deeper targets, and transducer resolution incapable of allowing identification of structures less than 1 mm in size (e.g. individual fascicles within the nerve) (Abdallah et al. 2016).

These challenges are being addressed, particularly with the advent of artificial intelligence (AI). Recent publications have incorporated AI software capable of identifying and delineating muscles, fasciae, blood vessels, and nerves to assist the anesthetist in image interpretation and subsequent nerve block performance (Figure 1.2) (Bowness et al. 2021). The benefits of such technology, particularly in the training of new regional anesthetists, are just starting to be recognized and appreciated.

SUMMARY

The evolution of ultrasound-guided regional anesthesia has soundly inserted itself into veterinary medicine. With a trajectory in line with its development in human medicine, the expectation can only be to assume that ultrasound guidance will phase out older technologies and become the new standard of care when performing regional anesthesia and analgesia in veterinary patients.

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Use of Ultrasound for Locoregional Anesthesia

CHAPTER 2

Matt Read, Micheál Ó Cathasaigh, and Luis Campoy

INTRODUCTION

Over the last 20 years, advances in ultrasound technology, including improvements in resolution and enhancements in image processing power and software, have allowed ultrasound-guided locoregional anesthetic techniques to evolve to where we are today in terms of the number of different techniques that are performed and the effects that can be appreciated in terms of efficacy of anesthesia and analgesia, efficiency of performance, and effects on reducing complications and enhancing patient safety (Griffin and Nicholls 2010; Neal 2016; Neal et al. 2016; Wang et al. 2017; Barrington and Uda 2018). Many of the regional anesthetic techniques that have been developed for use in humans are also applicable to veterinary species and can be used effectively and safely in animals to provide anesthesia and analgesia for a variety of painful procedures and conditions (Figure 2.1).

BASIC PHYSICS AND TECHNOLOGY

An ultrasound wave is a form of *acoustic* (mechanical) energy that travels as a longitudinal wave, interfacing with a continuous elastic medium (in the case of medical ultrasound, the body) by compression (areas of high pressure) and rarefaction (areas of low pressure) of that medium's particles. When discussing ultrasound and how it can be used in medical fields, it is useful to understand some basic terminology:

- ***Period*** – the time for a sound wave to complete one cycle, usually measured in microseconds (μs).
- ***Wavelength*** – the distance between pressure peaks, usually measured in nanometers (nm), (also referred to as "pulse length").
- ***Frequency*** – the number of pressure peaks per second, measured in Hertz (Hz).
- ***Acoustic velocity*** – the propagation velocity by which a sound wave travels through a medium, calculated as the product of frequency and wavelength. In the human body, this speed is fairly constant (~1540 $m\,s^{-1}$) (Sites et al. 2007a).

Medical ultrasound uses frequencies of sound (2–15 MHz) that are many times greater than those that are audible to the human ear (20 Hz–20 kHz). These ultrasound waves are created by passing an electric current through rows of piezoelectric crystals that are housed within an ultrasound transducer. Both natural and human-made materials, including quartz crystals and ceramic materials, can demonstrate piezoelectric properties. Recently, lead zirconate titanate has been used as piezoelectric material for medical imaging. By stacking piezoelectric elements into different layers within a transducer, electric energy can be transformed into mechanical oscillations more efficiently.

In order to generate an ultrasound image, these sound waves must bounce off tissues and return to the transducer. After generating an ultrasound wave, the transducer switches to receiving mode and waits until reflected waves return and vibrate the piezoelectric crystals, converting mechanical energy back into electrical energy. This information is then processed by a computer and signal intensity from regions within the area being scanned is converted into pixels whose brightness, based on an arbitrary gray scale, creates a 2-dimensional (2-D) image on the ultrasound screen that displays the cross-sectional anatomy from which the sound waves were returned. This process of transmission and reception is repeated by the transducer thousands of times every second, allowing the resulting images to be displayed in real time.

The number (and timing) of ultrasound waves that return to the transducer depends on the degree to which they are reflected off structures in the body. As ultrasound waves travel through the body, they interact with various tissues through *reflection*, *refraction*, *scatter,* and *attenuation*, depending on the physical properties of the tissues and the degree to which they prevent the transmission of ultrasound waves (Figure 2.2). Structures, such as nerves, are displayed more clearly, and hence, are easier to see when they are surrounded by tissues that have different acoustic impedances since the greater the difference(s), the easier it is for the ultrasound machine to process the information being returned to the

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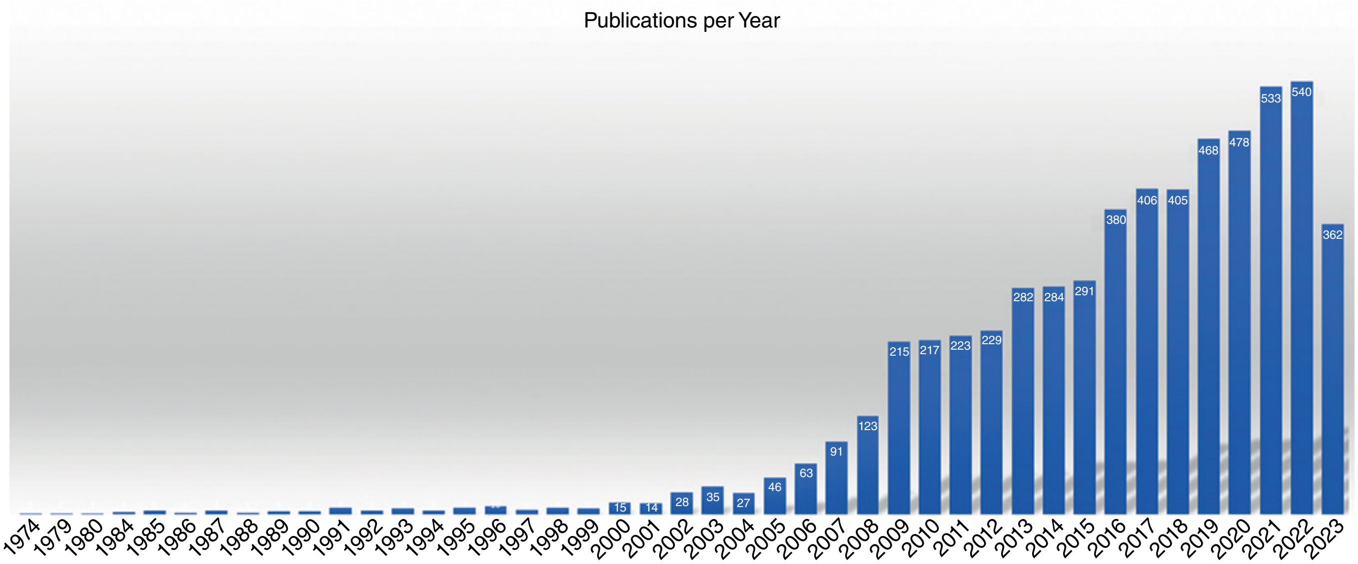

FIGURE 2.1 Graphical representation of the number of publications relating to ultrasound-guided regional anesthesia that enter the human and veterinary literature each year.

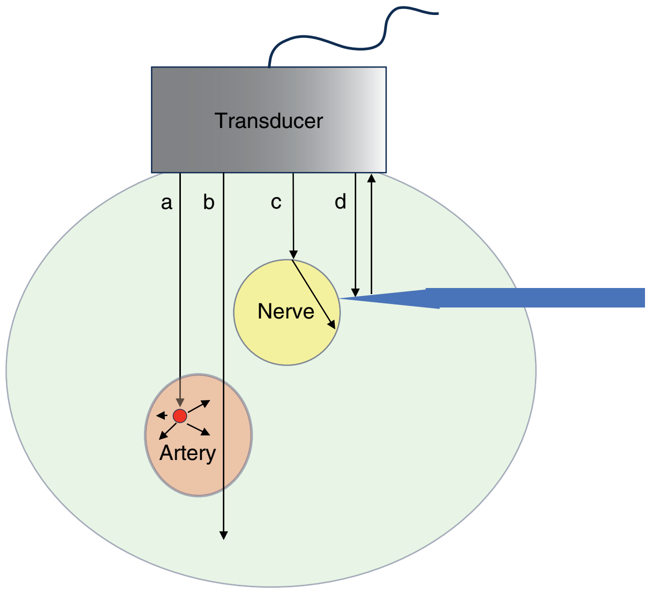

FIGURE 2.2 The many responses that an ultrasound wave produces when traveling through tissue. (a) Scatter reflection: the ultrasound wave is deflected in several random directions both to and away from the probe. Scattering occurs with small or irregular objects. (b) Transmission: the ultrasound wave continues through the tissue away from the probe. (c) Refraction: when an ultrasound wave contacts the interface between two media with different propagation velocities, the ultrasound wave is refracted (bent) depending upon the difference in velocities. (d) Specular reflection: reflection from a large, smooth object (such as a needle) which returns the ultrasound wave toward the probe when it is perpendicular to the ultrasound beam. Based on Sites et al. 2007a.

transducer (Sites et al. 2007a). The overall effect of these interactions is termed "*acoustic impedance*" and determines how many ultrasound waves are ultimately returned to the transducer to be processed.

As sound waves travel into the body, there is a progressive loss of acoustic energy as the waves pass through different tissues. This loss of energy is the result of the conversion of some of the mechanical energy into heat and is referred to as "*attenuation*." Different tissues cause loss of energy differently, which is based on their attenuation coefficient (measured as decibels per centimeter of tissue). The higher the attenuation coefficient of the tissue, the more the energy is lost (Table 2.1). When attenuation occurs, there is a coincident decrease in the intensity of the returning signal.

Higher-frequency waves undergo more attenuation than lower-frequency waves and, therefore, do not penetrate tissues as deeply (Figure 2.3). Settings on the ultrasound machine may need to be adjusted to artificially increase the signal intensity of these returning echoes so they can be

Table 2.1 Attenuation coefficients of different tissues (at 1 MHz).

Material	dB cm^{-1}
Bone	20
Air	12
Muscle	1.2
Fat	0.6
Blood	0.2

Source: Sites et al. (2007a)/BMJ Publishing Group Ltd.

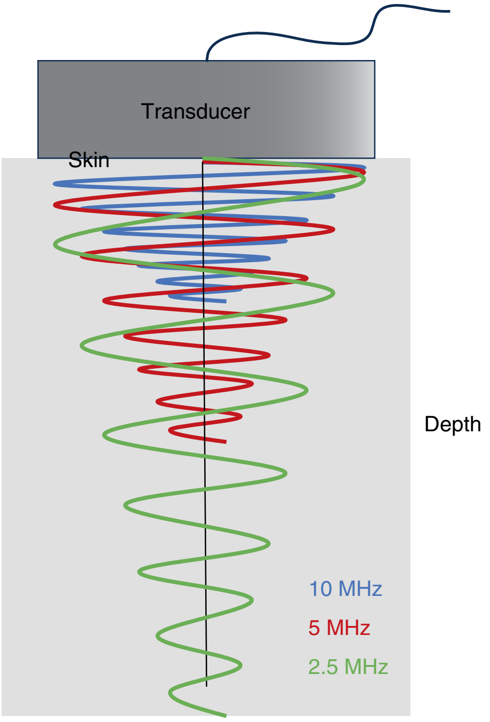

FIGURE 2.3 Attenuation (energy loss) is directly proportional to the frequency of the sound waves and the distance that the sound waves must travel. Note how the lower-frequency US waves are less attenuated compared with the higher-frequency (10 MHz) wave at any given distance (depth). Based on Brull et al. 2010.

processed into useful information for the user (see *image optimization*, below) (Sites et al. 2007a).

The final image that is produced is dependent on the number of waves that are returned to the transducer (which, in turn, is governed by the acoustic impedance of each tissue, as well the differences in impedances between different tissues) and the time it takes for those waves to return (i.e. longer return times are interpreted by the computer as being reflected by objects that are located farther away/deeper in the scan field).

The number and intensity of sound waves that are received by the transducer determine the "*echogenicity*" (brightness) of the reflecting object when it is displayed on the ultrasound screen. Brighter objects (referred to as being "*hyperechoic*") are associated with the return of more waves and, conversely, darker objects (referred to as being "*hypoechoic*") or black objects (referred to as being "*anechoic*") are associated with the return of fewer or no waves, respectively. For example, the acoustic impedance of air and bone (Table 2.1) causes reflection of a large proportion of the sound waves, which creates a bright, hyperechoic structure on the ultrasound screen. Hypoechoic tissues are those that tend to have greater water content, allowing the sound waves to travel through them more easily so fewer waves are reflected and received as echoes by the transducer.

IMAGE QUALITY

Image quality, or "*resolution*," refers to an ultrasound machine's ability to distinguish between different objects and tissues, ultimately determining the amount of detail that can be captured and subsequently displayed as an image. When it comes to performing regional anesthesia, the most important types of resolution to understand are:

- *Spatial* (axial and lateral)
- *Contrast*
- *Temporal*

Spatial Resolution

"*Spatial resolution*" refers to the ability of the ultrasound machine to differentiate between two different, but closely spaced, structures as being separate, discrete objects. This is determined primarily by the *axial* and *lateral* resolutions of the ultrasound beam, which are affected by different aspects of the physics related to use of ultrasonography.

Axial resolution refers to the ability of the ultrasound machine to discern two structures that are located along/parallel to the direction of the ultrasound beam (i.e. overlapping but at different depths from one another) (Brull et al. 2010) (Figure 2.4). Axial resolution is roughly equal to ½ of the pulse length, such that if the distance between the two objects is greater than ½ of the length of the ultrasound pulse, they will appear as two discrete structures on the screen (Sites et al. 2007a).

$$\text{Axial resolution} = \text{Wavelength} \times \text{Number of cycles per pulse}/2$$

The number of cycles within a pulse is determined by the damping characteristics of the transducer and is usually preset between two and four by the manufacturer of the ultrasound machine. For example, if a 2 MHz ultrasound transducer is used for scanning, the axial resolution would be between 0.8 and 1.6 mm, making it impossible to visualize a 21-gauge needle. Constant acoustic velocity, higher-frequency, ultrasound transducers can detect very small objects and provide images with better resolution. Thankfully, the axial resolution of current ultrasound systems is between 0.05 and 0.5 mm, making needles easier to see than when using earlier machines.

Using high-frequency (shorter pulse lengths) ultrasound waves will result in the highest degree of axial resolution, the most detail, and the best image quality. However, as described above, high-frequency waves are subject to the highest degree of attenuation (i.e. from both scatter and absorption), resulting in overall poor tissue penetration and the inability to provide information about deeper structures. This is why most high frequency (10–15 MHz) transducers,

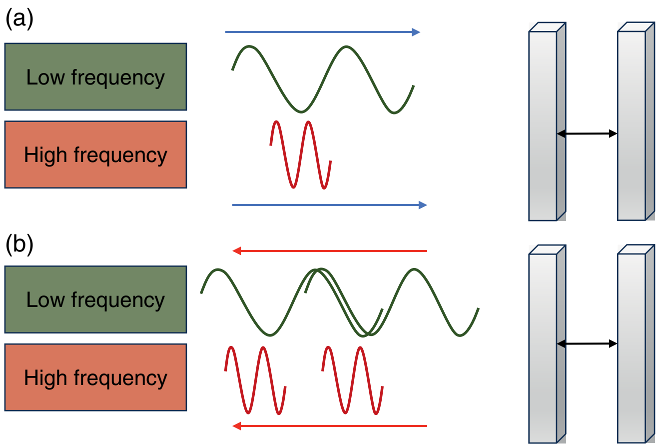

FIGURE 2.4 Axial resolution is the ability to discern objects in-line with the axis of the ultrasound beam. The axial resolution of an ultrasound wave is dependent upon wavelength, frequency, and the speed of ultrasound in tissue. Axial resolution is roughly described as one-half of the pulse length in mm. (a) A low-frequency and a high-frequency pulse propagating toward two rectangular objects. (b) The waves returning toward the probe following the reflection off of the objects. The blue arrows depict the ultrasound pulse traveling toward the two objects and the red arrows depict the ultrasound traveling back toward the transducer. The lower-frequency ultrasound has a wavelength that is larger than the distance between the objects (indicated by the black arrows), therefore, the returning signal from both objects will overlap and the probe will interpret this signal as coming from a single object. The higher-frequency pulse discerns two separate objects because the wavelength is much shorter than the distance between the two objects and the returning waves will not overlap. Based on Sites et al. 2007a.

while very good at imaging superficial objects at target depths of up to 3–4 cm (such as most peripheral nerves in dogs and cats), are unable to effectively image structures deeper than 6 cm.

When using ultrasound to perform nerve blocks, there is always going to be a trade-off between maximizing the axial resolution of the machine and the depth of penetration of the ultrasound waves. For this reason, it is important for the regional anesthetist to find the optimal balance between using the highest possible frequency, while still obtaining information about the target structures that are located at a particular depth (Brull et al. 2010).

Based on the depth of the target structure(s), the anesthetist should initially choose the appropriate transducer for the intended purpose (i.e. one with a high- [8–15 MHz], medium- [6–10 MHz], or low- [2–5 MHz] frequency ranges], with the next step being selection of the specific frequency of ultrasound waves to be emitted. Many ultrasound machines now allow the user to adjust the transducer frequency during use. For example, on some machines (e.g. Sonosite), the user can select between the low-, mid-, or high-end of the transducer's stated frequency range by selecting the PEN (penetration), GEN (general), or RES (resolution) settings, respectively (Brull et al. 2010).

Lateral resolution refers to the ability of the ultrasound machine to discern two closely spaced objects as being distinct from each other when they lie perpendicular to the beam direction (i.e. beside each other at the same depth) (Sites et al. 2007a) (Figure 2.5). Even though the user sees a 2-D image on the screen, the ultrasound waves that are generated by the transducer are actually being emitted in three dimensions. These waves have a self-focusing effect, which refers to the natural narrowing of the ultrasound beam at a certain distance/depth where the waves converge toward each other slightly before diverging as they transmit further into the body (Figure 2.6). Conceptually, targets could be missed if they were small enough to "slip in between" the incoming ultrasound waves if the beam was divergent. By using the concept of "*focus*," the user can minimize the chances of this occurring and make sure that lateral resolution is maximized in the area of interest.

Since the emitted waves are closest together at the narrowest part of the ultrasound beam, this area has the highest degree of lateral resolution and is referred to as the "*focal" or "transition zone*." The relative position of the focal/transition zone leads to the commonly used terms of "*near field*" (also called the Fresnel zone) and "*far field*" (also called the Fraunhofer zone). Some ultrasound machines allow the user to manually adjust and set the focal zone (as indicated by a marker/arrow on the side of the screen) to match the depth of the structure(s) they are most interested in. In the case of

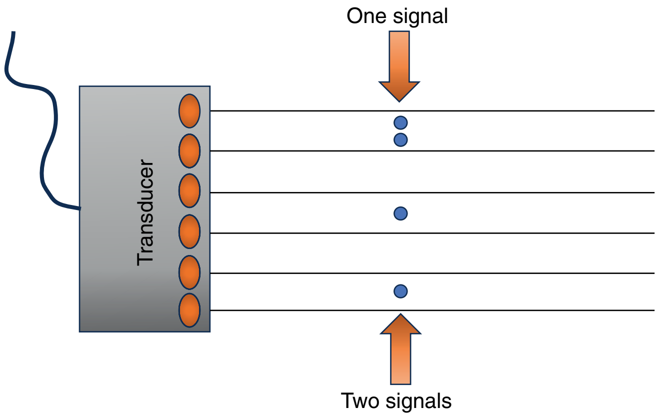

FIGURE 2.5 Lateral resolution is demonstrated here for a hypothetical linear ultrasound transducer. The ability of the ultrasound machine to correctly display two objects as separate structures depends on the relative distance between individual piezoelectric crystals versus the distance between the objects. The top two structures in this example will be imaged as one structure because each falls within surrounding crystal beams. The red ovals indicate individual piezoelectric crystals. For illustration purposes, this figure represents a fictitious situation in which there is no focal zone or divergence of the ultrasound beam. Based on Sites et al. 2007a.

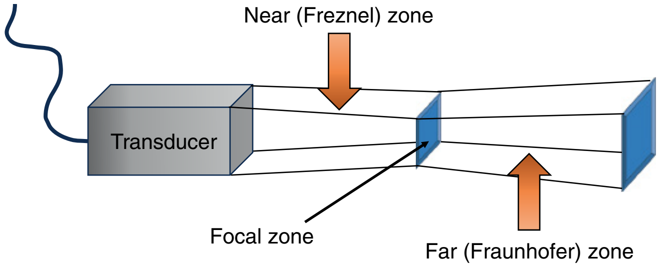

FIGURE 2.6 Characteristics of an ultrasound beam. The focal zone is where the ultrasound beam width is narrowest and demarcates the near zone (Fresnel zone) from the far zone (Fraunhofer zone). It is also the area with the best lateral resolution because the beam width is the narrowest at this location. Once the beam extends beyond the focal zone, lateral resolution begins to deteriorate due to divergence. This figure represents a prototypical electronically focused ultrasound beam. Based on Sites et al. 2007a.

many newer ultrasound machines, the focal zone is automatically set to be in the center of the screen so manual adjustments are not necessary. Instead, when using these ultrasound machines, the user simply needs to adjust the depth controls to position the area of interest (i.e. the target nerve in the case of regional anesthesia) in the center of the screen where the lateral resolution would be expected to be the highest. This way, very small objects will be more easily seen as discrete structures and the anesthetist will be able to better visualize important structures related to the block.

Contrast Resolution

"*Contrast resolution*" refers to the various shades of grey that are seen on the screen and is the ability of the ultrasound machine to distinguish between the different echo amplitudes that are returned from adjacent structures or tissues that have different characteristics. The more shades of gray that are able to be displayed on the screen, the higher the quality of the image.

Temporal Resolution

"*Temporal resolution*" relates to the inherent frame rate of the ultrasound machine, which is a measure of how quickly it can produce consecutive images (Sites et al. 2007a). The higher the frame rate, the more easily the machine will be able to accurately distinguish between events that are closely spaced in time, such as movements of a structure in real time (e.g. movement of a needle or a local anesthetic being injected). If frame rate is slow, there will be more blurring when motion is observed in the scan field, leading to a vaguer image.

Frame rate is related to the sweep speed of the ultrasound beam since sound waves are generated as adjacent/neighboring crystals are activated across the face of the transducer. The speed with which a sound wave transmits through the body's tissues and is reflected back to the transducer limits sweep speed since deeper tissues will reflect the beam after more of a delay than shallower structures, and the next wave cannot be generated by a crystal until the preceding crystal receives its echo (Sites et al. 2007a). This is another good reason for the user to set the scan depth just below the target of interest – if beams are able to be reflected sooner, temporal resolution can be maximized.

Based on the same principle, if the local anesthetic solution is injected too quickly, movement in the surrounding tissues will be detected, resulting in blurring of the image around the target. Injections should be performed slowly to avoid this artifact. Images reconstructed in real time can have a temporal resolution of approximately 30 frames per second. Modern scanners collect multiple scan lines simultaneously with frame rates of approximately 70–80 frames per second.

COLOR DOPPLER

The "*Doppler effect*" describes the change in the frequency of a sound wave that results from the wave being reflected back to a stationary listener (in this case the transducer) from an object that is in motion (e.g. blood). Ultrasound machines utilize this principle by assessing the change(s) in frequency as sound waves are reflected back from moving red blood cells and superimposing this additional information on the existing real-time 2-D image, allowing the user to identify and quantify the direction and velocity of blood flow in the area being assessed (Brull et al. 2010) (Figure 2.7).

If red blood cells are moving toward the transducer, the frequency of the reflected echoes will be higher than the original sound wave (the sound waves have to be squeezed) and the received sound will have a higher pitch ("*positive* Doppler shift"). If the red blood cells are moving away from the transducer, the frequency of the reflected echoes will be lower than the original sound wave (the sound waves have to be stretched) and the received sound will have a lower pitch ("*negative* Doppler shift"). This is the reason behind the

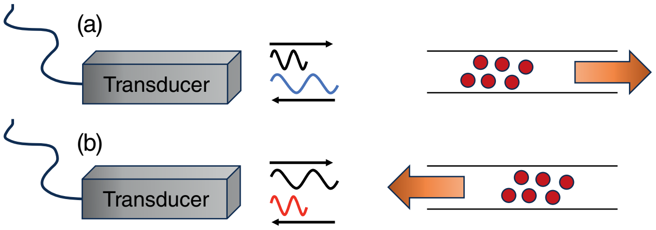

FIGURE 2.7 The Doppler effect. Doppler is used to measure velocity and directionality of objects. In the body, Doppler is most commonly used to measure velocity of blood flow. (a) The signal from fluid moving away from the probe will return at a lower frequency than the original emitted signal. (b) The signal contacting fluid moving toward the probe will return at a higher frequency than the original emitted signal. It is also important to note that the cosine of 0° is 1 and the cosine of 90° is 0. Therefore, as the angle approaches 90°, large errors are introduced into the Doppler equation.Based on Sites et al. 2007a.

sound of a siren changing as it first approaches a listener and then passes by and moves away from them. The Doppler equation states:

$$\text{Frequency shift} = \left(2 \cdot V \cdot F_1\right)\left(\text{cosine}\,\theta\right)/c$$

where V is the velocity of the moving object, F_1 is the frequency of the transmitted ultrasound waves, θ is the angle of incidence of the ultrasound waves and the direction of blood flow, and c is the speed of the ultrasound waves in the tissues of interest. Since the magnitude of a Doppler shift depends on the incident angle between the emitted ultrasound beam and the moving reflectors (e.g. red blood cells when imaging a blood vessel), if the transducer is oriented nearly perpendicular or perpendicular to the vessel (i.e. at a 90° angle), there will be no Doppler shift since the cosine of 90° is zero. As a result, there will not appear to be any flow through the vessel and it will appear on the ultrasound screen as being black. When the angle is 0° or 180° (i.e. the beam is nearly parallel to the movement of the object), the largest degree of Doppler shift will be detected. For this reason, when imaging an area for suspected vessels, the transducer should be manipulated through the use of tilting (see *image optimization*, below) in order to change the angle of incidence and make sure that an error is not inadvertently made in missing the presence of a vessel in the area of the needle's planned trajectory.

Although the Doppler shift can be used to calculate both the speed of blood flow as well as the direction of blood flow (i.e. during echocardiography), these measurements are less of a priority during the performance of regional anesthesia. For the regional anesthetist, the most important use of color Doppler (also referred to as color velocity Doppler) is the ability to confirm the absence of blood flow within their planned needle path (Sites et al. 2007a; Brull et al. 2010). For this reason, color Doppler is commonly used to scan for vessels within the area of the anticipated needle trajectory since small, hypoechoic vessels look very similar to small, hypoechoic nerves when using the standard gray scale.

It is a common misconception of novices that, when using color Doppler, *red* denotes arterial flow and *blue* denotes venous flow, however, this is not always the case (Figure 2.8). Instead, the common convention has it that blood flow moving toward the transducer is assigned shades of red, while blood flow moving away from the transducer is assigned shades of blue. For this reason, if the transducer is facing "down" the direction of arterial flow, movement within the vessel will still appear blue, even though it is an artery. When using color Doppler before performing a nerve block (e.g. on a limb), it can be useful to tilt the transducer toward the heart slightly, ensuring that pulsatile arterial flow appears red, and making it easier to correlate the color of the flow with the structure it is expected to relate to.

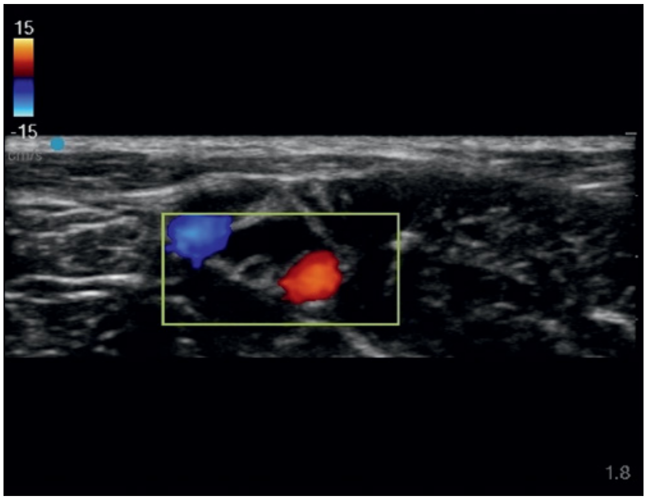

FIGURE 2.8 Ultrasonographic image of the relevant area following administration of local anesthetic for a proximal RUMM block in a dog. Color Doppler is being used to assess the intensity and direction of blood flow in order to identify the axillary artery (red) and axillary vein (blue).

A second form of Doppler, known as "*Color Power Doppler*," (CPD) is up to five times more sensitive in detecting blood flow than traditional color Doppler, but it does not provide information on the direction of flow. For this reason, CPD is particularly useful for assessing an area of the patient for very small vessels that would otherwise be difficult or impossible to see using standard color Doppler. As described above, while one limitation of using traditional color Doppler is the relationship between the angle of the ultrasound beam relative to the direction of blood flow, CPD functions almost independent of this limitation and the angle of incidence does not affect signal strength.

Since CPD does not provide information about the direction of movement (i.e. using red and blue), it uses an orange scale to indicate the intensity of the Doppler signal (Figure 2.9). Since CPD is so acutely sensitive to movement, to prevent artifacts from being introduced due to motion, the

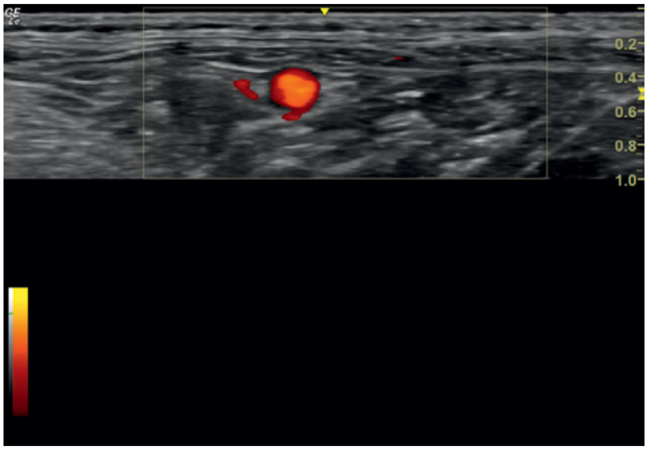

FIGURE 2.9 Ultrasonographic image demonstrating the use of CPD to indicate blood flow in the femoral artery during performance of a saphenous nerve block in a dog. Source: Berit Fischer.