The Association of Anaesthetists
of Great Britain & Ireland

WILEY-BLACKWELL

AAGBI Core Topics in Anaesthesia 2012

Edited by Ian Johnston, William Harrop-Griffiths & Leslie Gemmell

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A John Wiley & Sons, Ltd., Publication

Wiley-Blackwell is an imprint of John Wiley & Sons, formed by the merger of Wiley's global Scientific, Technical and Medical business with Blackwell Publishing.

Registered Office
John Wiley & Sons, Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

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9600 Garsington Road, Oxford, OX4 2DQ, UK
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350 Main Street, Malden, MA 02148-5020, USA

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Library of Congress Cataloging-in-Publication Data

AAGBI core topics / edited by Ian G. Johnston, William Harrop-Griffiths, Leslie Gemmell.
p. cm.
Association of Anaesthetists of Great Britain and Ireland core topics
Core topics
Includes bibliographical references and index.
ISBN-13: 978-0-470-65862-8 (pbk. : alk. paper)
ISBN-10: 0-470-65862-2 (pbk. : alk. paper)
1. Anesthesia. 2. Surgery, Operative. 3. Operations, Surgical. I. Johnston, Ian G. II. Harrop-Griffiths, William. III. Gemmell, Leslie. IV. Association of Anaesthetists of Great Britain and Ireland. V. Title: Association of Anaesthetists of Great Britain and Ireland core topics. VI. Title: Core topics.
[DNLM: 1. Anesthesia–methods. 2. Anesthesia–contraindications. 3. Surgical Procedures, Operative. WO 200]
RD81.A23 2012
617.9'6–dc23

2011024801

A catalogue record for this book is available from the British Library.

Set in 9.5/13pt Meridien by SPi Publisher Services, Pondicherry, India

1 2012

Contents

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Foreword

Iain Wilson, President of AAGBI

The Association of Anaesthetists of Great Britain and Ireland has worked tirelessly since 1932 to promote and advance patient safety by offering anaesthetists the educational materials they need to support safe and effective practice. Until recently, most of our educational output took the form of the journal *Anaesthesia*, Seminars at 21 Portland Place, London, and meetings such as WSM London and the Annual Congress. However, times change and the AAGBI is well placed to adapt to changing times and the changing needs of its members. The development of the appraisal process, the start of Revalidation and the introduction of the CPD Matrix have all changed the way that Consultant Anaesthetists and Specialty Doctors need to structure and record their learning and continuous professional development.

Two years ago, we started a highly successful series of Core Topics Meetings that are held in towns and cities throughout the UK and Ireland. Our new website will give us opportunities to develop and deliver online education, and the Tutorial of the Week developed in collaboration with the World Federation of Societies of Anaesthesiologists is already available in pdf format from www.aagbi.org. This Core Topics book is another way in which we are offering the very best of educational material free of charge to our members. We have asked acknowledged experts to write concise and informative articles on topics that really are core to the safe delivery of patient care: difficult airways, pain management, hip fractures and obstetric haemorrhage to mention but four.

We know that our members use different educational material in different ways, and we think that even in a world of smart phones, blogs and social networking, many anaesthetists still favour the portability, convenience – and legibility – of a book. We are therefore offering this Core Topics book free of charge to our members to gauge how well it is received. We will be asking you for your feedback and, if it is positive and encouraging, we will consider creating a regular series of publications such as this.

I hope you enjoy reading this AAGBI Core Topics in Anaesthesia book. If you have any comments to make about it, any suggestions for future topics or if you would like to offer to write an article for us, please email me at president@aagbi.org.

CHAPTER 1

The Physics of Ultrasound

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Key points

- Ultrasound is a high-frequency pressure energy wave transmitted longitudinally through the soft tissues of the body.
- Advances in computer technology have made medical ultrasound possible by processing millions of signals every second.
- Ultrasound makes it possible to examine most of the tissues of the body safely and easily.
- The pressure, energy and heating effects of clinical ultrasound devices have not been shown to damage normal biological tissues.
- The ultrasound wave must be reflected off a tissue interface at right angles. This means that a combination of good hand–eye coordination and correct positioning of the probe is the basis of a good image.
- Images are presented as patterns on a greyscale monitor. Pattern recognition is therefore the basis of the interpretation of these images.
- The B or brightness mode gives a greyscale image that is distorted because of a loss of reflected echoes by scatter and refraction.
- Doppler shift is caused by a change in wavelength when fluid such as blood is moving towards or away from the ultrasound wave.

This chapter aims to give an introduction to the basic physics of ultrasound in order to allow the reader to understand how images are produced and hence how to obtain the best images when using ultrasound. Clinical ultrasound devices simultaneously produce and transmit multiple pressure waves, and receive and rapidly interpret the many attenuated, returning pressure wave signals. The pressure wave signals are converted into electrical signals. The production of an image in real time by a portable scanner has only become possible with the development of the microprocessor chip. A modern ultrasound device has a lot of computing power with many microprocessors performing many billion operations per second, which makes it possible to build up complicated images in real time.

AAGBI Core Topics in Anaesthesia, First Edition. Edited by Ian Johnston, William Harrop-Griffiths and Leslie Gemmell.

In the near future, smaller processors will enable more precise images to be created on smaller, lighter and cheaper devices.

Sound energy

Sound is energy in the form of a pressure wave. This mechanical energy displaces molecules that press against adjacent molecules and pass the energy on in waves, while the first molecules to be compressed together return to their original configuration. Ultrasound waves travel in a longitudinal direction, rather like a piston pumping in and out, producing a series of high pressure, unidirectional waves in front of the piston. The effect can be visualised as the energy of the wind blowing through a cornfield. The corn bends over but returns to the upright as the wind blows through the field. The pressure recorded in ultrasound waves can be as high as 10 times atmospheric pressure but it is a transient change. A sound wave needs molecules to pass the wave on so it cannot travel through a vacuum, and medical ultrasound does not pass air so, for instance, the lung will appear black unless there is an effusion or consolidation within the lung. The principle behind obtaining information using ultrasound is to send a short burst of pressure waves into the tissue, wait for the initial wave to bounce back from a number of tissue interfaces, and then analyse the waves that return. This can be understood with reference to the early application of sound waves in Sonar. A single wave of sound is sent out from a boat into the water and the time taken for the echo to return is measured. Knowing the speed of sound in water and the time taken for the sound to return, the distance travelled by the sound can be calculated; the point at which the sound is reflected is half this distance.

Generation of the ultrasound wave

In order to build up an image of the tissues, it is necessary to have many sound waves transmitted from a series of points fixed in relationship to each other. This is made possible with a line or array of transducers in the probe head. The probe is the most delicate part of the device and a typical array contains 128–256 transducer elements in a wide aperture device. There are matrix arrays now on the market with up to 2400 transducer elements. Each transducer has a dual function. It both creates and sends out a short burst of ultrasound pressure waves, and is then silent until it detects those waves returning. This is referred to as pulsed ultrasound. Small groups of transducers are activated in turn to emit at the same time followed by another group. In this way some part of the probe head is always emitting and some part is always receiving. In order to build up an image, it is necessary to emit and receive many signals in a short period of time. This is made possible by the use of materials that exhibit the piezoelectric effect. Pierre and Jacques Curie found that a crystal of quartz changes shape when an electrical charge or voltage is applied across it and, conversely, when pressure is applied to the crystal, it changes its shape and an electrical charge is created. This two-way process of an electrical charge causing a change in shape that produces a pressure wave, and pressure causing a change in shape that creates an electrical charge, is known as the piezoelectric effect. The emitted ultrasound signal is produced by applying an electrical charge to the transducer and the returning pressure wave distorts the transducer to create an electrical charge that can then be processed. The sensitivity of the transducer has been increased by replacing quartz crystals with materials such as lead zirconate titanate (PZT) mixed with epoxy, and polyvinylidene difluoride (PVDF). The transducer is made by heating powdered PZT to above its Curie temperature (365°C for PZT), sometimes mixed with epoxy to make a composite ceramic. While the crystals are hot and mobile a high voltage current is applied across the transducer to polarise the crystals so that they line up to give a maximum response to changes when an external electrical charge or pressure is applied. The voltage is maintained until the mixture cools and solidifies so that the alignment of the crystals is preserved in the solid state.

Refinements in transducer production

Each transducer has a particular frequency at which it will convert electrical energy into sound waves and vice versa. This is the *resonance frequency*, which is mostly dependent on the thickness of the transducer element: the thinner the element, the higher the frequency. In practice, the emitted wave is not a single wavelength but a spectrum of frequencies. These are produced by forming multiple matching layers on the surface of the element. These layers also provide good sound transmission between the transducer and the soft tissues over a range of frequencies. Modern transducers are constructed of piezoelectric materials that have similar acoustic impedances to that of soft tissue so that sound is not lost by reflection at the soft tissue-transducer interface.

The frequency, wavelength and speed of sound waves

A sound wave has characteristics of frequency, wavelength and speed. The frequency and speed of the sound wave determine the type of substance through which it will travel.

Frequency

The frequency (f) is the number of high-pressure waves in one second. The time taken from one high pressure to the next high pressure is known as the *period* (T). Therefore, $T = 1/f$

Frequency is quoted in Hz where 1 Hz = 1 cycle.s^{-1}. Low-frequency sound waves or *seismic* waves are transmitted through dense materials such as the earth. Sound waves that are below the audible range are called *infrasonic*. Sound that is heard has a frequency in the range 20 Hz to 20 kHz. This is called the *audible frequency range*. Audible sound waves are transmitted through air at a speed of 330 m.s^{-1}. Ultrasound has a frequency above the audible range at 20 kHz. Clinical ultrasound is in the range of 2–15 MHz. This is transmitted well through the soft tissues of the body. Air-filled cavities and solid material such as bone and metal needles will not transmit this frequency of sound, so the lung and intracranial structures cannot be examined, except in babies when ultrasound can be focused through the fontanelles.

Wavelength

The wavelength (λ) is the distance between two high-pressure peaks in the sound wave. The wavelength is the speed of the sound wave divided by the frequency of the high-pressure components, hence $\lambda = c/f$. The wavelength is important for *spatial resolution*. This is the ability to identify two objects when one is deeper than the other (longitudinal spatial resolution) or side-by-side (axial spatial resolution) but only separated by a short distance. In soft tissues, wavelengths of about 1 mm are used (at 2 MHz the wavelength is 0.77 mm). A higher frequency produces a shorter wavelength. The width of the wave is about the same as the wavelength, so the width of the sound wave becomes smaller as the frequency increases. If the object presents a surface area that is less than the width of the sound wave, such as a red blood cell, the wave will not be reflected at 180°.

Speed

The speed of the sound wave is determined by the nature of the substance or organ it passes through. The speed $c = \sqrt{B/\rho}$, where B is the stiffness or *bulk modulus* and ρ is the density of the tissue or organ. The optimum speeds of sound for the different soft tissues of the body are:

- liver 1580 m.s^{-1}
- muscle 1575 m.s^{-1}
- blood 1570 m.s^{-1}
- water 1480 m.s^{-1}
- fat 1430 m.s^{-1}

A convention exists in which manufacturers of medical ultrasound devices all use the same sound wave speed to allow images to be comparable. This speed is 1540 m.s^{-1}. Therefore, clinical ultrasound will not pass through materials that require a much higher or lower speed for wave transmission:

- air 330 m.s^{-1}
- lead 1240 m.s^{-1}
- bone 2800 m.s^{-1}
- skull bone 4080 m.s^{-1}
- aluminum 6400 m.s^{-1}

Medical ultrasound waves are all reflected off the surface of normal bone, so the internal structure of bone cannot be examined. It is possible to diagnose a fracture by examining the surface image of the bone, which may become irregular at the fracture site, or the clear surface image may be lost, indicating that the sound waves are entering the haematoma produced by the fracture. Needles are metal but unlike bone a clear surface image will not be seen because the surface area is small and curved, so very little of the wave will be focused on the needle and, even if it is focused it, will then be scattered into the tissue (see *axial resolution* and *scatter* below).

The fundamental properties of medical ultrasound are therefore:

- speed = 1540 m.s^{-1}
- frequency (f) = 2–12 MHz
- wavelength (λ) = 0.1–0.8 mm

The image

The image is presented as a greyscale. By convention, each returning signal lightens the black of the screen, with strong echoes showing as white and no echo as black. To get the best image, as much energy as possible in the emitted waves needs to return to the detector.

Reduced and distorted images

Various distortions cause a loss of the energy in the emitted waves and a weaker wave returning to the detector. This leads to a reduced or distorted image. The probe must be in close contact with the skin, as ultrasound does not pass through air. The use of a gel ensures good transmission of waves from probe to the tissue. The probe should be at right angles to the skin and the tissue plane to be examined, except for a Doppler shift examination. When the energy wave meets an interface between two tissues, the beam is either reflected, refracted or scattered into many directions. As the ultrasound wave passes through any tissue, some energy is also lost by