Reviewing the curriculum for physics and technology in postgraduate sonography courses

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Abstract

Physics and technology is seen as a difficult subject by those training in medical ultrasound. The reasons for this are discussed. Who should teach the subject and what should be included are considered. Ways to approach the subject so as to make it more relevant and easier to learn are proposed and a basic syllabus is suggested in an appendix.

Keywords: Ultrasound education, teaching, physics, technology

Ultrasound 2015; **23**: 42–47. DOI: 10.1177/1742271X14567499

Introduction

The study of physics and technology of ultrasound should form a key underpinning theoretical basis for anyone using diagnostic or therapeutic ultrasound in clinical practice. For convenience, we refer to all such users as sonographers. In most cases, they are not physicists or engineers but clinical practitioners who need to have an applied working knowledge and understanding of the physics and technology behind the ultrasound equipment they use. For many trainees, the physics and technology module on their postgraduate course is one they often struggle with and maybe spend a disproportionate amount of time in absorbing and understanding the content. Therefore, a valid question to raise is 'How much physics and technology does a sonographer need to know?' Looking at the future, now is a good time to review what should form a basic, minimum curriculum. There are a number of factors that suggest this is a worthwhile exercise as becomes clear when the issues are outlined. Over the last 30 years, a lot of work has been done, mainly in the United States, in the field known as Physics Education Research. This has looked at why students find physics a hard subject and what may be done to improve its teaching. An early example of this work was that by Arons.^{1–3} More recent summaries of this work, together with ideas of how to apply the findings of the research, are given by Knight⁴ and Redish.⁵ The study by Redish has been used to inform the discussion given here.

Why is physics and technology necessary?

The question of the necessity of studying the physics and technology of ultrasound for a sonographer can be answered in two ways. One way is to say that modern ultrasound scanners take care of everything and it is no longer

necessary to cover very much physics of ultrasound at all. The machine pre-sets will tune the machine for the particular scan and for the difficult to scan patient. Gain and image appearance are automatically set up with another control. Doppler measurements are made automatically and the sonographer can be shown what knob to turn to get a certain effect without knowing what it is doing to the machine or image signal. With the accessibility of cheaper portable scanners there are many healthcare personnel scanning in precisely this way today. The other way to answer the question is to say that in order to get the best from the scan it is necessary to know in greater detail, how the scanner works and how ultrasound interacts with tissue in the body. The interaction of ultrasound with tissue is the essence of ultrasound image formation and only by understanding that interaction can images be fully interpreted and artefacts understood. Being able to answer such questions as – 'Why are some types of fatty tissue more likely to give poor visualisation than others?', 'What are the things I must do to improve frame rate and why?', 'What determines what is a safe regime to work with when scanning sensitive tissue such as the eye?' – requires a certain level of knowledge and understanding of physics and technology. Most sonographers rightly consider themselves to be professional experts in ultrasound imaging. As professional experts in their field, having a good understanding of how their equipment works in order to get the best out of it, making informed diagnoses from images and understanding where new developments are coming from is surely a pre-requisite and a strong argument for covering physics and technology in their training. Ultrasound is a unique imaging modality in that anyone, given a probe and some gel, can produce an image. That is both its utility and its danger. The danger is not from a factor like ionising

radiation, but in not producing optimum images and interpreting them correctly, based on knowledge of anatomy, pathology and the physics of sound waves bouncing around the body. Having a good understanding of the physics and technology should be considered to be a clinical governance issue. If you do not understand what your equipment is doing to the patient, or know how it works, should you be applying it to the patient to get images you will interpret?

Why is physics and technology hard?

Many trainee sonographers find physics and technology difficult. For some, this in part arises from memories of the struggle they had with physics and technology at school. Even at school level, physics is often seen as a 'hard' subject and not pursued to a higher level. Why is this? Firstly, the subject is hierarchical in that it involves learning and understanding a lot of interrelated facts in which one part necessarily builds on another. Calculations with equations are performed to get further results, from which deductions about how things work and behave are made. Some struggle with handling and interpreting equations. It requires not just memory work, but applying concepts to solve problems. This is a different thought process to most other subjects and requires time and effort to engage with and absorb. It goes against the grain of wanting instant knowledge and information that can be repeated to pass an exam. The aim of teaching physics and technology to sonographers should not be so much in order to pass an exam, as to give a set of tools that can be used to solve problems in real life sonographic imaging. Analysis and problem solving is involved in many subjects, but school physics is often remembered as being particularly difficult, abstract and not seen as relevant to everyday life. This, then immediately produces a psychological barrier to the post-graduate student, who has not studied such a subject for many years.

The second reason it is found hard relates to how it is often taught. Some teachers make the subject hard. This may be by making the simple seem complex, and not making the complex simple, or by failing to relate the relevance of the material to everyday life, to everyday scanning. How physics and technology should be taught is an important question that we shall return to.

Thirdly, it is found to be hard because, quite simply, there are some difficult concepts within the subject that have to be tackled. They may be counter-intuitive or complex. Within medical ultrasound, one might think of the principle of harmonic imaging as an example. That is not a reason not to include them, but a challenge to the teacher to explain them as clearly as possible in a relevant context that can be understood. Physics and technology does require some careful and deep thinking and it is a discipline to learn to think that way.

Finally, putting these together, past difficulty of struggle with the subject, poor teaching and the fact that there are some real difficulties means a panic can set in and the student struggles again. So, in addition to any subject related difficulties there may be, there are motivational, emotional

and attitudinal difficulties internal to the student that overlie studying physics and technology. Once more it is a 'hard' subject. The students know they have to pass the module and at the same time are thinking it is largely irrelevant, difficult and barely worth the effort – Why do we have to do this?

Who teaches physics and technology?

Another factor making teaching physics and technology a pertinent question at this time is the question of who will teach them. Until now, most Higher Education Institutions (HEI) have been able to engage people with a physics background to teach these modules. These have mainly been drawn from the health service or from within health related academia. This may still be possible in the future. However, over the last 30 years ultrasound has matured as an imaging modality, with only the large manufacturing companies able to invest the time and resources to develop it further. As a consequence, many of those who started out with a physics background working in the National Health Service developing new techniques are reaching retirement and are not being replaced by ultrasound physicists. In future, physics and technology modules may more often be taught by those for whom physics is not so deeply embedded in their background and who may therefore find greater difficulty in teaching the subject, or have less enthusiasm for doing so. This then impacts on how physics and technology are taught and what content should be included. It is to be hoped that some within the profession will take a sufficient interest in the subject that they make it their business to become more proficient and good communicators of it. It is still a sound dictum in education that if you wish to teach a subject at one level, you need to understand it at a much deeper level in order to teach clearly at the level needed. One source of teachers may be those physicists who have studied the imaging with non-ionising radiation module within the physicist Modernising Scientific Careers Scientist Training Programme (STP), or those who have covered it in depth in one of the other STP programmes such as vascular science.⁶

What should be covered – how should it be taught?

That then leaves the questions of syllabus content and method of teaching. What physics and technology does a practising sonographer need to know, understand and be able to apply in their daily work? A full physics and technology course in medical ultrasound would include theoretical concepts, equations and mathematical descriptions of these concepts and the ability to apply that knowledge to finding and developing practical solutions to constructing equipment, and analysing the results of ultrasound interaction with tissue. Sonographers require a more limited syllabus that will include some of these features to a greater or lesser extent. Within the United Kingdom, postgraduate sonography training in the universities is accredited by the Consortium for the Accreditation of Sonographic Education (CASE).⁷ Their remit is to ensure that the courses

are capable of producing sonographers who are competent to practise in a clinical service. The CASE Handbook includes, as a core topic area it expects to see on any course it accredits, teaching on 'Science and technology'. The handbook gives a brief indication of typical subject areas that may be included, but does not go so far as to give a detailed minimum syllabus. There is very little else published regarding what should be in a science and technology module for sonographers. There are a number of text books covering the relevant ground, some with more depth than others.⁸⁻¹¹ As an example of what is currently taught, the text 'Ultrasound Physics and Technology – How, Why and When'⁸ was written to match the syllabus at one HEI in the United Kingdom.

Any syllabus for sonographers needs to be guided by two key questions. (A) Why does the sonographer need to know this, and (B) at what depth do they need to know this? A working sonographer needs a good understanding of basic concepts related to driving the scanner, interpreting images and understanding the differences between machines as presented by the manufacturers. Driving the scanner includes both getting the best quality images possible and doing so safely. This, for example, would include selecting an appropriate frequency, setting output power and gain correctly and setting the focal zone(s) to the depth(s) of interest. 'Safely' implies knowledge of the fact that ultrasound deposits energy into tissue with possible deleterious effects and the guidance provided by the mechanical and thermal indices.¹² Interpreting images includes knowing the limitations of what is seen and the recognition of artefacts and their causes. This requires an understanding of resolution, the nature of speckle and the presence of noise in an image. It also includes a knowledge of the assumptions in ultrasound scanning such as straight line travel of the pulse, infinitesimal beam width, etc., the physical failure of which give rise to artefacts that may be seen. Being able to discuss machines with manufacturers is an important part of procurement and understanding new features as they are introduced. Such discussions can be carried out far more intelligently if the sonographer is able to relate what is new on a scanner to how an earlier version worked. These all go toward being able to discuss results and findings with colleagues in the health service that provide the expertise expected of those whose profession is sonography.

The emphasis needs to be on basic physical concepts and their real world implications for scanning. This does not need to be very mathematical. Simple equations and calculations may be given for illustration of values, for example, speeds of sound together with frequency and wavelength, percentage reflectances between different tissue types, resolution limits that can be expected for different frequencies, etc. For Doppler work, the Doppler equation should be understood, as should an understanding of aliasing. Detailed understanding of how equipment is engineered is not needed; block diagrams of function are probably sufficient.

The importance of constantly linking the content to examples from life is vital as it helps to anchor the concepts and show them to be relevant. It connects new information to existing knowledge, a key educational principle.⁵ For

example, in considering a piston as a transducer and source of sound waves, the piezoelectric transducer of ultrasound may be compared to the membrane of a loud-speaker, which all students will be familiar with, or a PZT transducer element resonating and having to be damped to give a short pulse may be likened to pinging an empty wine glass with and without holding onto its rim. In teaching the content at a conceptual, rather than mathematical or engineering level, the content becomes a story that can easily be related to daily practice and also illustrated by everyday examples from life. For example, when talking about attenuation, one might do so in terms of the 'journey taken by the pulse' as it travels through the body. Describing why making a measurement of circumference one way might be more accurate than another can be likened to walking round a garden or comparing the garden to a standard shape, etc. If well illustrated by clear diagrams, this becomes more memorable and what may originally have been seen as a difficult module, is seen to be clear, logical and relevant.

When it comes to illustrating how these principles operate in practice and what effect adjusting the controls actually has on an image, simple experiments with phantoms or standard clinical views can be devised. A number of such basic experiments/illustrations are described in Kofler et al.¹³ Students can be led to understanding through guided questioning, in which they have to think through to the answer themselves.¹⁴ If the student can perform, describe and explain what they see, they demonstrate a practical understanding of the taught physics and technology. This is the real aim of teaching the subject to sonographers and this last part, of the student explaining back what they see, is important in the whole education process. In assessing how well the concepts have been understood in a way that can be practically applied, it is important to get such regular feedback from the student.⁵ Can they summarise, in their own words, to one of their colleagues? Can they make a decision regarding scanner settings based on what they know is going on physically in the scanner and to the sound waves? Do they recognise an artefact and can they explain why it occurs, and how to overcome it? Can they say why a cheap portable scanner might perform differently to a high end one, based on what they know about imaging technology? Where a number is calculated, can they say whether the answer is sensible?

With a well chosen syllabus, the teaching of physics and technology is entirely relevant to everyday sonography and, if well taught, should be seen to be so by the student. There will be areas of debate as to whether a particular topic or detail is included, but all should be guided by the two key questions given above. A suggested minimum syllabus for postgraduate sonographers is given in an appendix. The order and manner in which any syllabus is covered will vary but the content topics are listed with suggested range/depth of coverage.

DECLARATIONS

Competing interests: The author has no conflicts of interest to declare.

Funding: This work received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Ethical approval: Not applicable

Guarantor: CPO

Contributorship: CP Oates is the sole author.

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Appendix

A basic physics and technology syllabus for sonographers

Basic physics

Sound wave $c = f \times \lambda$	Oscillatory motion of molecules about an average position with the disturbance propagating – definition of f , λ , c and amplitude – phase is also useful here
Pulse-echo principle Ultrasound pulse and concept of a beam	$\Delta t = 2d/c$ Corridor that the pulse travels and along which echoes return – level of detail on beam shape (?)
Refraction	Snell's law may be given but the concept and physical examples are the key
Specular reflection	Depends on density and speed of sound as measured differences in

Scattering and speckle	medium – angle of reflection – examples given as % reflection – the term acoustic impedance may be introduced but deep understanding of excess pressure and particle velocity not needed – need for acoustic gel on skin Concept of superposition of waves introduced – depends on frequency and scatterer size – depends on tissue structure but does not show tissue microscopic structure
Attenuation	Summary of losses along the sound beam to noise level defining maximum penetration
Resolution	Concept of smallest target resolvable – needed for 'what is a valid measurement' – depends on pulse length, beam width and frequency – example values – need for focusing
Focusing	Principle – weak or strong – effect on resolution out of focal zone
Frequency /transmit power relationship of resolution and attenuation (penetration)	

Basic technology

Piezo-electric effect	
Bandwidth	Concept related to 'wide band transducers' – advantages – good resolution, allow advanced processing e.g. harmonics
Basic transducer construction	Block diagram – including backing layer for short pulse = 'wide band' and principle of matching layer
A-mode, B-mode, M-mode	
Linear and sector format, curvilinear and endoprobe formats	
Stepped linear array field	Principle of real time electronic sweep of image plane
Phased array and electronic beam steering	Show using block diagram of time delays and resulting wave front directions
Electronic focusing versus fixed focus lens	Show using block diagram of time delays and resulting wave front directions
Multi-zone focusing	In receive and transmit – penalty on frame rate for transmit
Gain/TGC	Transmit power, overall gain and time gain compensation effect on image

Frame averaging/persistence		Aliasing and Nyquist limit	Concept of unambiguous detection of Doppler frequency/velocity – use of scale/PRF control
Compounding	Spatial and frequency – advantages of filling in curved surfaces – speckle smoothing	Duplex scanning with angle correction	Combining anatomy and function to give non-invasive velocity measurement
Grey scale mapping	Contrast versus smooth image – dynamic range	Doppler measurements	Accuracy/sources of error – angle error – scale-Doppler gain – indices – autotrace function
Read and write zoom	Could include interlacing and effect on frame rate	Colour Doppler ultrasound	Basic process – frame rates – detailed methods of detection probably not needed – poorer spatial resolution than B-mode
Controls	Ensuring all the practical aspects of understanding the physical concepts are able to be properly applied to driving the scanner	Frame rate	Colour box size – scale
Making measurements	Methods and potential errors in longitudinal, circumferential, area and volume measurement	Aliasing and interpretation of colour	Average velocity shown – change in direction – high velocities
Slice thickness, 1D, 1.5D and 2D arrays	Also include 4D scanning	Power Doppler	
Grey scale artefacts	Discuss based on assumptions in ultrasound i.e. $c = \text{const}$, uniform attenuation, straight line propagation, infinitesimal beam width – some are clinically useful	CDU display sensitivity	Doppler signal amplitude threshold – scale – beam steering versus heel and toe of probe
Poor visualisation	Factors affecting visualisation including – differences in density within fatty tissue – artefacts – transmission windows	Doppler artefacts	Pulsed Doppler and colour – wall thump filter
		Controls	Ensuring all the practical aspects of understanding the physical concepts are able to be properly applied to driving the scanner
Safety and QA		Advanced topics	
Safety	Thermal and mechanical effects of ultrasound	Harmonics	Simplified principles – energy into double frequency mode – detected with wideband transducer and filters – pulse subtraction – advantages and disadvantages
Power and intensity	Proportional to amplitude squared	Advanced processing	Auto-TGC, image smoothing algorithms, pulse coded excitation
MI and TI	Definitions and application	Tissue Doppler imaging/speckle tracking	Including advanced analysis of tissue motion for cardiac work
Basic QA principles	Quick check methods of transducer function – infection control, etc.	Principle of synthetic aperture imaging	
Doppler ultrasound		Contrast ultrasound	Bubbles in the sound field – pulse inversion – flash techniques
Doppler effect	Doppler equation including $\cos\theta$ and its significance for measuring velocities non-invasively	Elastography	Methods – principles and application
CW Doppler	E.g. pencil probe – no range discrimination – no frequency/velocity limitation	3-D Ultrasound	3D image manipulation – surface rendering – segmentation and volume measurements – 3D colour Doppler
Principle of detection	In broad terms – block diagram – bidirectional detection		
The sonogram display	Instantaneous power spectrum – amplitude versus frequency/velocity – sonogram plots how this varies over time – basic understanding of what the sonogram shows – e.g. velocity profile, turbulence	General	
Pulsed Doppler	Range gating	Terms and names	Review the names and terms used by different manufacturers for their controls i.e. the same control may have several proprietary names

Notes

- a. This syllabus includes the basic fundamentals that are needed to have a working understanding of ultrasound physics and technology as is needed in day-to-day sonographer practice. Additionally some advanced topics are included. Some topics traditionally taught have been omitted – should they be included? For example, decibel notation. Others have been treated in less detail e.g. acoustic impedance and how much detail to cover on beam shapes.
- b. Those studying vascular or cardiac modules will need more on Doppler e.g. average velocity measurement, volume flow calculation, manual versus auto trace for Doppler measurements, intrinsic spectral broadening.
- c. Those studying vascular or cardiac modules will need a full coverage of haemodynamics in the specialist module.