Ultrasonics in Clinical Diagnosis

EDITED BY
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PREFACE

Ultrasonic techniques have been developed during the past twenty years so that they now have an established place in clinical diagnosis. These developments have been described in papers published in specialised scientific journals and books, but until now there has been no single book which presents a survey of the basic principles and the whole field of practical clinical application. This book sets out to fill this gap, and to be at the same time a review, a textbook, a reference book, and a source of references.

The aim of the book is to cover the ground in adequate depth to satisfy the needs of candidates for the examination for the Fellowship of the Faculty of Radiologists, and for the Higher Examination of the Society of Radiographers. It should also be useful reading for DMRD and MSR candidates, for medical specialists in various fields, and for hospital physicists.

The technological development of ultrasonic diagnostic methods has reached an important stage. What could be termed the *conventional* techniques are described in this book: fresh clinical applications are possible, but there is little scope for technological innovation. The present generation of instruments will doubtless be improved in detail; but the performances of the best of them are already approaching the optimum. Progress in instrumentation now depends upon the employment of new systems, perhaps based on computers, or holography, or spectroscopy. For this reason, it will be some years before significant changes are likely to take place in the methods which are now used in clinical practice, and which are described here.

It has been a most agreeable task for me to prepare for publication the contributions of my friends and colleagues. There is a danger that a book composed to separate contributions may seem to be a collection of disjointed papers. I have tried to avoid this by sometimes drastic editing, and I am especially grateful to my friends for having allowed their manuscripts to be submitted to this indignity. I am confident that each of the contributed chapters is a distinguished and definitive review of its own specialised topic, and I hope that the authors' individual styles may have escaped unharmed by my amendments.

My debt to the contributors is very great. But the publication of this book would not have been possible without the help and encouragement of many others. Dr. H. F. Freundlich has always provided the facilities of his Department, his friendly criticism, and his wise guidance, in the work with which I have been associated in Bristol. This work has been made possible only by the support of the Medical Research Council, the Department of Health and Social Security, and the Board of Governors of the United Bristol Hospitals. I cannot overemphasise the value of discussions with many colleagues, particularly Professor K. T. Evans, Mr. D. H. Follett, Mr. M. Halliwell and Professor A. E. A. Read. Mrs. Anita Rawcliffe cheerfully prepared the typescript from sometimes very scruffy pages. The staff of Churchill Livingstone have been both courteous and helpful. Last but not least, my wife and family have been uncomplaining during many months of undeserved neglect.

P. N. T. WELLS

April 1972

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PART I

BASIC PRINCIPLES AND DIAGNOSTIC METHODS

Chapter 1

Basic Principles

P. N. T. Wells

Ultrasonic diagnosis depends upon physical measurements of the interactions between ultrasonic waves and biological materials. An adequate knowledge of the basic physical processes involved in the generation, propagation and detection of ultrasonic waves is necessary for a proper understanding of ultrasonic diagnostic techniques. The contents of this chapter are intended to provide this background, in the simplest way.

1.1. FUNDAMENTAL PHYSICS

1.1.*a*. WAVE MOTION

Ultrasound is a form of energy which consists of mechanical vibrations the frequencies of which lie above the range of human hearing. The lower frequency limit of the ultrasonic spectrum is generally taken to be about 20 kHz.* Most diagnostic applications employ frequencies in the range 1–15 MHz.

Ultrasonic energy travels through a medium in the form of a *wave*. Although a number of different wave *modes* are possible, almost all diagnostic applications involve the use of *longitudinal* waves. The particles† of which the medium is composed vibrate backwards and forwards about their mean positions, so that energy is transferred through the medium in a direction parallel to that of the oscillations of the particles. The particles themselves do not move through the medium, but simply vibrate to and fro. Thus, the energy is transferred in the form of a disturbance in the equilibrium arrangement of the medium, without any bodily transfer of matter.

* 1 Hz (hertz) = 1 cycle per second. Thus, 1 kHz = 1000 cycles per second; 1 MHz = 1 000 000 cycles per second.

† A *particle* is a volume element which is large enough to contain many millions of molecules, so that it is continuous with its surroundings; but it is so small that quantities variable within the medium (such as pressure) are constant within the particle.

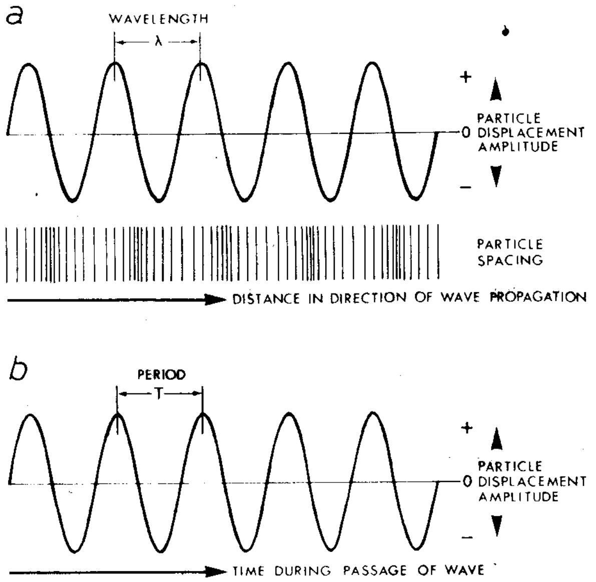

Fig. 1.1. Diagrams illustrating longitudinal wave motion. (*a*) Particle displacement amplitude and particle spacing at a particular instant in time in the ultrasonic field: these diagrams represent the distribution of the wave in *space*. (*b*) Particle displacement amplitude at a particular point in space in the ultrasonic field: this diagram represents the distribution of the wave in *time*.

In an ultrasonic field, cyclical oscillations occur both in space and in time: the simplest type is illustrated in Fig. 1.1. The oscillations here are continuous at constant amplitude, and the particles move with *simple harmonic motion*: when a particle is displaced from its equilibrium position it experiences a restoring force which is proportional to its displacement. This *direct proportionality* is the characteristic which distinguishes simple harmonic motion from other, more complicated, disturbances. The *wavelength*, λ, is the distance in the medium between consecutive particles where the displacement amplitudes are identical; similarly, the wave *period*, T, is the time which is required for the wave to move forward through a distance λ in the medium. The *frequency*, f, of the wave is equal to the number of cycles which pass a given point in the medium in unit time (usually one second); thus,

$$f = 1/T \tag{1.1}$$

The wavelength and the frequency are related to the propagation velocity, c, by the equation

$$c = f\lambda \tag{1.2}$$

For example at a frequency of 1 MHz, the wavelength in water (c = 1500 ms^{-1}) is 0·15 cm.

These relationships apply strictly only to continuous waves of constant amplitude. Other types of disturbance (for example, pulsed waves) are not associated with a single frequency, and so λ and T are not constants (c is largely independent of frequency).

The velocity at which the energy is transferred through the medium is determined by the delay which occurs between the movements of neighbouring particles. This depends upon the *elasticity*, K, (because this controls the force for a given displacement in the medium) and the *density*, ρ, (which controls the acceleration for a given force within the medium), according to the equation

$$c = \sqrt{(K/\rho)} \tag{1.3}$$

Table 1.1. Ultrasonic properties of some common materials, including biological tissues.

	Propagation velocity m s^{-1}	Absorption coefficient at 1 MHz dB cm^{-1}
Air	330	12
Blood	1570	0·2
Brain	1540	0·9
Fat	1450	0·6
Human soft tissue, mean value	1540	0·8
Kidney	1560	1·0
Liver	1550	0·9
Muscle, mean value	1590	2·3
Skull-bone	4080	13
Water	1480	0·002

The velocities in soft tissues are closely similar, but that in bone is higher: typical values are given in Table 1.1.

1.1.*b*. BEHAVIOUR AT BOUNDARIES

When a wave meets the boundary between two media at normal incidence, it is propagated without deviation into the second

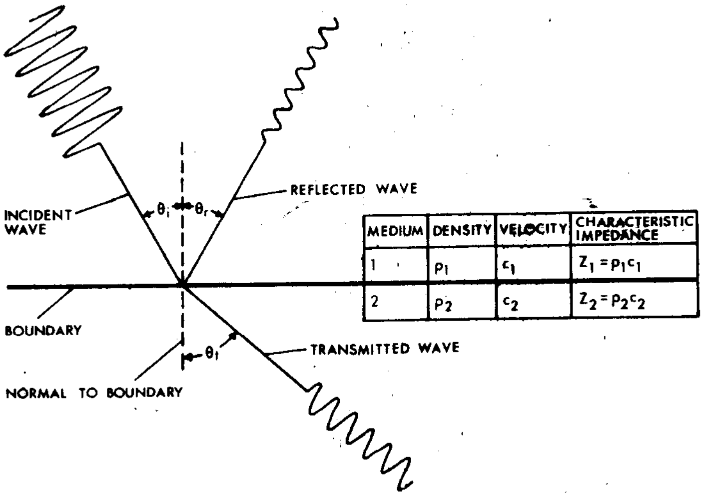

Fig. 1.2. Diagram illustrating the behaviour of a wave incident on the boundary between two media.

medium. At oblique incidence (Fig. 1.2), the wave is deviated by *refraction* unless the velocities in the two media are equal. The relationship is

$$\frac{\sin\theta_i}{\sin\theta_t} = \frac{c_1}{c_2} \tag{1.4}$$

Sometimes a fraction of the incident wave is reflected at the boundary. In such cases, $\theta_i = \theta_r$, and the reflection is said to be "*specular*".

In any given medium, the ratio of the instantaneous values of particle pressure and velocity is a constant. This constant is called the "*characteristic impedance*", Z, of the medium, and it is related to the density and velocity by the equation

$$Z = \rho c \tag{1.5}$$

In a propagating wave, there are no sudden discontinuities in either particle velocity or particle pressure. Consequently, when a wave meets the boundary between two media, both the particle velocity and the pressure are continuous across the boundary. Physically, this ensures that the two media remain in contact. However, in each medium, the ratio of the particle pressure and velocity is fixed and equal to the corresponding characteristic impedance. If the characteristic impedances are equal, the wave travels across the boundary unaffected by the change in the supporting medium (apart from deviation by refraction, if the velocities differ, and the incidence is not normal). However, if the characteristic impedances are unequal, the incident energy is shared between waves reflected and transmitted at the boundary so as to satisfy the conditional requirements in the relationships between the particle pressures and velocities. Because velocity is a directional quantity, whereas pressure is not, the calculation requires that account should be taken of the angle of incidence at the boundary. The most useful result is that corresponding to normal incidence: in this case, the fraction, R, of the incident energy which is reflected is given by the equation

$$R = [(Z_2 - Z_1)/(Z_2 + Z_1)]^2 \tag{1.6}$$

If $Z_1 = Z_2$, $R = 0$: thus, there is no reflection at a boundary between media of equal characteristic impedance. However, if $Z_2 \ll Z_1$ (for example, at the interface between a liquid and a gas), then $R \simeq 1$, corresponding to almost complete reflection.

It is important to realise that the results of calculations of refraction and reflection conditions at a plane boundary may not apply to a similar characteristic impedance discontinuity at a rough interface or a small obstacle. The specular component of reflection is replaced, by an amount depending upon the geometrical characteristics of the discontinuity, by components of scattered energy. This effect becomes important when the dimensions of the discontinuity are in the order of a wavelength or less. If the obstacle is very much less than a wavelength in size, the intensity of the wave which returns to the source (for given conditions of characteristic impedance) varies inversely as the fourth power of the wavelength. However, the theoretical problem of the behaviour of a wave at a boundary with wavelength-order discontinuities is enormously difficult. Unfortunately, this may be the situation at many of the boundaries in biological tissues, and in such cases it is generally