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# The Future of Ultrasonics in Diagnostic Medicine [and Discussion]

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# The future of ultrasonics in diagnostic medicine

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Ultrasonics has been the poor relation of twentieth century physics and it is only recently that thought has been given to investigating the scientific basis of ultrasonic diagnostic methods. The physics of acoustic wave interactions with human tissues is complex but suggests the existence of a rich supply of diagnostically useful information.

Static imaging technology may now be approaching a resolution limit imposed by variability of refractive index in overlying tissues, but advances are to be expected in the direction of quantification of the imaging process. Supplementary information on fine structure of tissues is also to be expected from the application of analytical techniques, of which frequency dependence of backscattering and diffraction pseudo-crystallography are two examples in which there is current research interest. Recent rapid advances in dynamic or 'real time' imaging reflect the potential of ultrasound for providing hitherto unobtainable information on patterns of tissue movement both in health and disease.

Major advances in application will come, in many areas of medicine, simply as good equipment, experience and expertise become more generally available but particular impact from scientific advances may occur in the diagnosis and management of both cardiovascular disease and cancer, with effective early detection of breast cancer being one of a number of distant but compelling prospects.

## Introduction

Any attempt to predict the future of an applied science must necessarily be speculative and can only be of real value to the extent that it is based on existing facts. Thus the principal objectives of medicine are the prevention and effective treatment of disease and, although the correlation may be imperfect, a useful indication of the balance between different classes of serious disease can be obtained from mortality statistics. A summary of these data for England and Wales in 1975 is shown in table 1.

These figures provide a salutary reminder of the numerical importance, in modern Western society, of cardiovascular disease and cancer. Both classes of disease present problems in diagnosis which cannot be dealt with by existing methods and for which ultrasonic methods are likely to prove particularly effective. At the other extreme, the mortality statistics reflect the relatively advanced state of modern obstetric medicine, which was the first major speciality to employ ultrasound as a routine diagnostic method. Another, and compatible, commentary on these latter figures might be that obstetrics is likely to decline in relative, although not absolute, importance in the spectrum of diagnostic applications of ultrasound.

The science of ultrasonics has suffered by being one of the poor relations of twentieth century physics. Thus, particularly perhaps in the U.K., ultrasonics has played a very small part in the research and teaching work of academic physics and, in relation to the applications of physics to diagnostic medicine, serious interest was virtually non-existent until a few years ago. Recently, scientific interest has been awakened and the technological basis of the subject has also started to develop very rapidly. One fairly safe prediction, therefore, is that considerable scientific and technological developments are in store, although the precise direction and limits of such developments may not be easy to foresee.

Table 1. Causes of mortality, England and Wales, 1975†

| | total deaths | percentage |
|---|---|---|
| circulatory system disease | 300000 | 51 |
| neoplasms | 124000 | 21 |
| respiratory system disease | 81000 | 14 |
| accidents | 21000 | 4 |
| perinatal causes | 4000 | 0.72 |
| pregnancy and childbirth | 77 | 0.01 |
| Other | 53000 | 9 |
| | **583000** | **100** |

† Based on the Registrar General's *Review on deaths by cause, sex and age in England and Wales*, 1975 (London: H.M.S.O.).

Table 2. Static acoustic parameters of tissues potentially measurable *in vivo*

backscattering coefficient, $\sigma$
frequency dependence of $\sigma$
orientation dependence of $\sigma$
angular dependence of scattering
attenuation coefficient, $\mu$
frequency dependence of $\mu$
orientation dependence of $\mu$
acoustic velocity

## Scientific background

Medical imaging by the ultrasonic pulse–echo method has been practised for some 25 years but the physical principles involved are still not fully understood. Recent research and theoretical analysis has, however, highlighted the importance of scattering of ultrasonic waves by the structural elements of tissues (Hill 1978). Structures whose magnitude and characteristic separation distances are comparable to an ultrasonic wavelength (typically 0.1–1.0 mm) are likely to cause diffractive scattering. Their physical identity is uncertain but appears to be related to the collagen-containing connective tissue network whose detailed spatial arrangement is characteristic of a particular tissue type.

This provides the basis for one rather specific differentiation in the acoustic properties of different anatomical structures which could have considerable diagnostic value. There are many independent acoustic properties which can be measured by remote ultrasonic means and thus used either to characterize and identify a particular target element or to image a complete section of anatomy in a quantitative and unambiguous manner (table 2). The backscattering coefficient, measured at a given frequency, is a quantity, of basic importance in pulse–echo investigations, that can be expected to be related uniquely to other physical properties of a target tissue. It is currently used in an empirical manner to distinguish different tissues in terms of a 'grey level scale' (Kossoff *et al.* 1976). However, with existing techniques, backscattering coefficient is never truly separated from the effects of attenuation in the target and intervening tissue, although reconstruction methods of effecting such a separation are being investigated (Duck & Hill 1978).

The frequency dependence of backscattering coefficient is determined independently and thus potentially provides independent information (Nicholas 1976). This has been applied by Lizzi *et al.* (1976) in investigations of disease of the eye and orbit.

Owing to the predominant influence, in many situations, of diffractive contributions to scattering, both backscattering coefficient and its frequency dependence can be defined only in statistical terms. If the backscattered intensity is examined in relation to the orientation between the interrogating beam axis and the target structure, there is generally a characteristic relation. This phenomenon is analogous to crystallographic X-ray diffraction, and is also being investigated for its diagnostic value (Huggins & Phelps 1977). Again, it appears possible to extract from such diffraction data measurements characteristic of the target tissues (Nicholas & Hill 1975). The diffractive nature of ultrasonic scattering by biological tissue expresses itself in a variety of ways and additional information about tissue structure is obtainable from studies of angular (i.e. angles not 180°) scattering dependence (Gramiak *et al.* 1976).

Superficially it may seem somewhat surprising, in view of its importance in X-ray imaging, that attenuation has played such a small part in ultrasonic diagnostics. This seems to be for two reasons: the scarcity of anatomical sites in the human through which transmission of ultrasound is practicable and the degrading effects on transmission images of reflexion, refraction and phase cancellation artefacts. Solutions to these problems have recently been proposed by J. G. Miller (personal communication) while backscatter reconstruction (Duck & Hill 1978) appears to offer an approach to the determination of attenuation in organs through which transmission is impossible. It is possible in principle to determine the frequency dependence of attenuation, which might give independent information about the nature of the structure examined.

Certain tissues, particularly skeletal muscle, and to a lesser extent myocardium and other fibrous tissues, exhibit appreciable mechanical anisotropy. It has been suspected for some time that a corresponding anisotropy in ultrasonic attenuation would occur and this suspicion has recently been confirmed (D. Nassiri, personal communication).

Finally, it has been demonstrated (Greenleaf *et al.* 1975) that appreciable differences in sound velocity occur in different tissue types, thus laying the basis for a method of ultrasonic transmission reconstruction imaging. This may have some potential in breast tumour diagnosis (Glover 1977).

Exploitation of possibilities for remote, *in vivo* measurement of these various parameters provides the basis for a technology that has come to be termed 'tissue signature characterization' or, perhaps more elegantly, 'telehistology' (Chivers & Hill 1973).

## Organ and tissue dynamics

There is little detailed information on the patterns and extent of the tissue movements that occur and it is one of the main propositions of this paper that ultrasound can provide a unique means for investigating such movement and for exploiting the information for diagnostic purposes.

Cine-ultrasonography, or 'real time ultrasound', at frame rates of the order of 20 $s^{-1}$, is now a well-established technique that is yielding new information about the movement of a number of organs, and particularly the heart and the foetus. For many purposes this time resolution can be highly informative but if attention is to be concentrated on a limited region, as would be the case in particular for studying local properties of tissues rather than those of




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whole organs, repetition frequencies of about 2000 Hz are attainable. This possibility is already widely used, in the 'M-mode' ultrasound technique, for investigating the movements of heart valves. It has potential values for studies of tissue elasticity and vascularization. The former possibility has been investigated in infarcted and normal myocardium, which are different in their low-frequency elastic properties.

A specialized approach to extraction of information about the dynamic behaviour of certain tissues has been available now for some time in the form of Doppler signal processing. This simple technique has been very powerful in the analysis of blood flow. Such information is of value in the investigation of cardiovascular disease, and has recently been claimed to be capable of detecting the abnormal patterns of vascularization associated with many tumours (Wells *et al.* 1977). This could prove to have valuable applications in both the detection and management of malignant disease.

Doppler and M-mode signal processing have been the predominant practical approaches to ultrasonic analysis of tissue dynamics but it seems unlikely that either is capable of extracting all the useful information; a more generalized approach may well lead to further practical advances.

## Technological development

It is only recently that appreciable progress has been made in establishing a scientific basis for diagnostic ultrasound, and the technology of the subject is still largely empirical. Imaging is almost entirely based on the arbitrary but convenient process of recording, in their proper spatial relation, the amplitudes of returned echoes, rather than values of any specific parameter that has unique relation to a physical tissue property. Similarly, the detailed mode of operation of the central component of most diagnostic systems, the mechanically damped ferroelectric transducer, is still imperfectly understood, and systematic analysis of the pulsed acoustic field that it produces has only recently been attempted (Duck 1978).

In the past four years considerable advances have been made in the technology of ultrasonic imaging, particularly in the direction of improved spatial resolution and dynamic range. At present, rapid developments are occurring in techniques of cine-ultrasonography.

One of the remarkable features of ultrasound when compared with X-rays and radioisotopes is the high rate at which information can be generated (commonly of the order of $10^7$ bits $s^{-1}$). Ironically it seems to be largely as a result of this fact that advances have been relatively slow hitherto, by comparison with other modes of medical imaging, in two particular directions: the application of on-line digital processing techniques for information extraction, and the introduction of automation in scanning procedures.

An important factor determining the success of any medical technology is its cost, both in monetary terms and, often more critically, in the requirement for medical and technical skill in operation. Many ultrasonic techniques are relatively inexpensive to implement: simple Doppler instruments may cost £200 or so and a good pulse–echo tomographic imaging equipment will compare favourably even with most conventional X-ray or radioisotope imaging installations, particularly when the real total cost of radiation protection for the latter is taken into account. The main limitation hitherto in establishment of ultrasonic diagnostic services, particularly those involving imaging, has come from cost and availability of the necessary skilled staff. Hence the development of automatic techniques of image aquisition and simple diagnostic indicators may be of great significance.

## Scale and direction of future developments

Although the interaction of ultrasound and human tissues is still poorly understood, what is known is sufficient to establish the considerable potential of the subject in medical diagnosis. Far from approaching a plateau, it seems likely to be entering a very active phase of scientific and technical advance. Similarly, the technology of the subject is developing rapidly.

Ultrasound has particular contributions to offer in two major classes of disease: cancer and diseases of the cardiovascular system. Its potential contribution in cancer comes from the nature of its interactions with soft tissues and, in particular, from the possibility of extraction of detailed information on tissue structure. In cardiovascular disease its ability to derive information on dynamic functioning is particularly important. In both these areas ultrasound is capable of providing information that is not at present available, and is unlikely to be attainable by any other method.

Predictions, according to Francis Bacon, '... ought to serve but for winter talk by the fireside' and are ill suited to the cold print of scientific publication. Nevertheless, there are certain trends:

(1) Conventional static pulse–echo imaging will continue to develop in reliability, ease of use, technical performance (but perhaps not greatly in spatial resolution, where a refraction limitation is already apparent). The evolution of automatic (doctor-independent) scanning mechanisms together with skill and experience in interpreting high quality ultrasonic images, will be additional factors in extending practical application.

(2) Cine-ultrasonography ('real time' scanning) will develop rapidly towards the point where, at tolerable cost, imaging performance is comparable to good static techniques. It will then supersede conventional techniques with, perhaps, a degree of intermarriage stimulated by the need to delineate complete anatomical sections with clear reference marks.

(3) Telehistology (remote, *in vivo*, tissue characterization) will grow very considerably in importance, although this may take some time because it is based on poorly understood science and is likely to require fast, capacious and expensive information processing techniques.

(4) Quantitative analysis of tissue and organ movement may also, at least in the long term, grow very considerably but, as the dynamic manifestation of telehistology, it is subject to similar constraints and limitations on the rate of its growth.

(5) Three-dimensional imaging is unlikely to find wide application.

(6) Transmission imaging (including transmission holography) is likely to be of little value owing to the almost ubiquitous presence in the human body of bone and air obstructions. This applies also to transmission reconstruction techniques although reconstruction may have a useful role in the backscatter mode, where it can make possible quantitative imaging.

(7) The emphasis in the application of diagnostic ultrasound techniques will move further towards cancer and cardiovascular disease, both because of the needs in these areas and because of the inherent suitability of ultrasound to meet such needs. In both areas ultrasound has very interesting long-term potential as the basis for screening methods for early detection and diagnosis of major disease conditions.

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## *Discussion*

P. N. T. Wells (*Department of Medical Physics, Bristol General Hospital, Guinea Street, Bristol BS*1 6*SY, U.K.*). One of the important applications of diagnostic ultrasound is in the management of certain diseases and clinical conditions, such as cancer, arteriosclerosis and pregnancy, rather than merely in the detection or identification of disease.

C. R. Hill. I agree entirely. In fact my main ultrasound research grant at present is specifically directed at the 'investigation and management of cancer'.

R. C. Chivers (*Department of Physics, University of Surrey, Guildford, Surrey GU*2 5*XH, U.K.*). I should appreciate Dr Hill's comments on the suggestion that although the visualization is, as he suggested, close to the refractive limit, we have little hard evidence for the origin of the white dots of a B-scan; and further that lack of knowledge of the fundamental interactions between ultrasound and human tissue (the same interactions, incidentally, that lead to biological effects at high intensities) is a serious hindrance to standardization and automation since we are ignorant of the relative importance of fundamental, biological and technological limitations.

C. R. Hill. I have pointed out in my paper that, in spite of recent work, to which Dr Chivers has himself contributed, we lack information about fundamental interactions, although I should not agree that the group of interactions that are of relevance to visualization is necessarily identical to that responsible for biological effects of high intensity ultrasound. The particular question of the detailed appearance of the B-scan image is certainly an interesting one; recent work on diffractive nature of ultrasonic scattering by tissues gives us some clues (see, for example, Nicholas & Hill 1975), and a good discussion of this specific question is given by Burckhardt in a recent paper (1978, *IEEE Trans.* **SU-25**, 1–6).

P. N. T. Wells. Whenever ultrasound has been discussed during this meeting, it has always either been implied or stated that the receiving transducer has been of the phase-sensitive, amplitude detection type, such as the piezoelectric transducer. The signals thus detected and subsequently subjected to analysis may be significantly affected by the performance of the transducer. On way of getting around part of this problem is by the use of a transducer of the phase-insensitive, power detection type, such as the cadmium sulphide transducer. Does anyone here have experience of this?

D. O. Thompson. Research on power transducers is being pursued in the U.S. by several groups, including Dr J. Heymann at N.A.S.A. and Professor Miller's group at Washington University in St Louis. I suggest that there are applications in which these transducers are desirable, and there are those in which they are not, which rely on phase information.



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