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Apologia: how and why medical sonar developed

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Summary

The easiest part of any lengthy experiment is the idea. Its application is more difficult and most difficult of all is its financial support. This is the story of an experiment which developed as we groped our way over 18 years and in which most of the worthwhile observations were accidental and were not foreseen.

A man that looks on glass
On it may stay his eye
Or if he pleaseth through it pass
And then the heavens espy.
HYMN: GEORGE HERBERT 1593–1632

Accident and good luck have combined at the right time to open up for our profession a new diagnostic dimension. No credit can be claimed for what is after all a coincidence, but it is the purpose of this lecture to explain how it came to be exploited.

Some sort of apology, or at least an explanation, is due to my clinical colleagues. This lecture, given in memory of the great Victor Bonney, provides the opportunity. Not only did Bonney regard himself, and rightly so, as a pelvic surgeon but he put British gynaecological surgery squarely on the map. Under his influence it reached a peak of perfection as a technical art which has not been since surpassed. The need for it today is less challenging thanks to advances in modern radiotherapy and in endocrinology. Less, however, could be said for precision in diagnosis. Here, it is hoped, sonar may have something to contribute.

The title 'Apologia' is intended in the Socratic sense, although I hope that its consequences will not be as lethal to its author as Socrates' apology proved to be for him. It will be recalled that Socrates in his *Apologia* earned for himself more votes for his execution than were recorded by the same jury for the verdict which declared him guilty.

Breakthrough in gynaecology and obstetrics

In the early 1950s there was no apparatus commercially available for the medical uses of ultrasound. No engineering firm could be expected to interest itself in such a speculative venture until it was clear that there would be work available for apparatus on a scale sufficient to launch it on a naturally cautious market in medical instrumentation.

Since so little was known about the ultrasonic echo characteristics of tissues in vivo, results had first to be obtained quickly in a subject such as gynaecology, where tumour masses could be readily identified and the diagnoses confirmed at laparotomy within at most a few days. In contrast a case of hepatomegaly, for example in a medical ward

Victor Bonney lecture delivered on 31st October 1973

might not be confirmed by laparotomy or necropsy until a lapse of time had allowed its nature or its extent to alter beyond recognition.

We ourselves started our study of sonar in cases of gynaecological tumour masses, but this field alone would not have provided enough momentum to carry the subject through to industrial viability. It was its overflow into obstetrics which widened the use of sonar to such a remarkable and unforeseen extent that already a situation is developing in which any pregnant patient, at some time or another in her pregnancy and for one reason or another, may come under an ultrasonic probe.

Stage setting Sound waves, as is well known, can penetrate tissues far more efficiently than light. Ultrasonic waves—sound waves of a frequency far above the range of hearing—have the additional advantage that they can be directionally controlled.

For nearly a quarter of a century after Langevin's discoveries, which were only belatedly published some 10 years later[1], the echo-ranging principle was ignored in medicine. Dussik[2] in Austria first tried to use ultrasound in medical diagnosis, but instead of an echo-reflecting technique he attempted a through-transmission method in the case of the head and ran into insuperable difficulties.

Although the echo-ranging principle had come to be used for oceanographic survey, it was Firestone[3] in the United States who achieved the first great breakthrough with the echo principle in miniaturized form applied to engineering problems, this time under the stimulus of the Second World War. It thus became possible to examine metal structures without the need for cumbersome high-voltage X-rays. Flaw detection in metals was already established many years before medicine took an interest in the 1950s.

Among the earliest pioneers of echo-ranging in medicine were Wild[4] in Minneapolis and Reid[5], and in retrospect it is a pity that their first interest was in screening for malignant disease, including the breast. My own interest coincided with my translation in 1954 to Glasgow, a city with heavy engineering commitments. I was initially much exercised by the clinical problem of the grossly distended abdomen, whether from tumour, ascites, obesity, or a combination of any of the three. Some time later I learnt of Howry's genius[6] and work in the United States[7], which was cut short by his untimely death. His brilliant concept of sector scanning, however, involved immersing the patient in a tank of degassed water, which is hardly acceptable in the case of sick patients.

It was my good fortune to approach the subject through engineering channels in my city of adoption and I was able to borrow metal flaw-detecting equipment.

Landmarks The 21st July 1955 will always remain one of the sunniest and most important days in my life, when we took down to a factory research department in Renfrew two cars whose boots were loaded with recently excised fibroids, large, small, and calcified, and a very large ovarian cyst. My engineering friends thoughtfully produced a very large lump of steak as the control material. All I wanted to know, quite simply, was whether these various masses differed in their ultrasonic echo characteristics. The results were beyond my wildest dreams and even with the primitive apparatus of those days clearly showed that a cyst produced echoes only at depth from the near and far walls, whereas a solid tumour progressively attenuated echoes at increasing depths of penetration (Figs. 1 and 2). Furthermore, lower frequencies—for example, $1\frac{1}{2}$ MHz instead of $2\frac{1}{2}$ MHz—were necessary to pene-

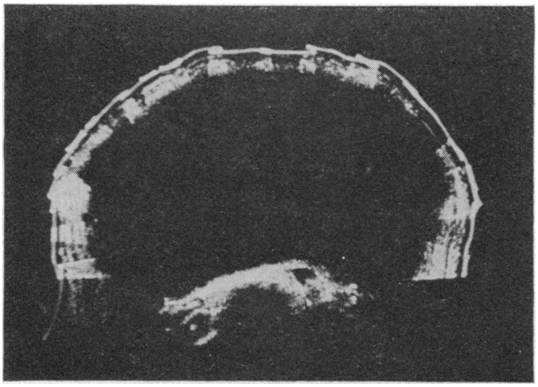

FIG. 1 *Huge ovarian cyst. Transverse section viewed from below upwards 8 cm above umbilicus. Note projection inwards from behind of vertebral column. 2½ MHz.*

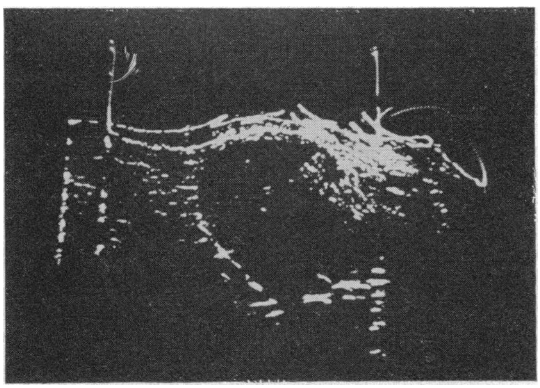

FIG. 2 *Large fibromyoma of uterus. Barely transonic at 1½ MHz. Vertical marks on the skin indicate position of umbilicus and symphysis pubis. This and all subsequent ultrasonograms taken in longitudinal section with the patient in the dorsal position, cephalad to the left.*

trate the denser types of tissue, such as an ovarian fibroma. From this observation it was immediately clear that here was a method not only of examining the anatomical structures of a tumour but also of assessing at least some of its physical characteristics. The large lump of steak, curiously enough, none would agree to take home.

Through the good offices of Dr Douglas Gordon, who at that time had already achieved results in the demonstration within the brain of midline shifts[8] in many cases of head injury, associated for example with subdural haematoma, it was agreed that we would take over a metal flaw detector with which Mayneord and Turnbull had been attempting to study the head at the then Royal Cancer Hospital. This machine was incapable of detecting anything within the range of the first 8 cm and it was necessary to use a stand-off technique through a water bath of even greater depth. It does not take much imagination to think of the bizarre situation of balancing a bucket with a plastic bottom and filled with water on top of a female abdomen smeared with coupling oil and then trying to interpret echoes using a probe dipped gingerly into the surface. Accidents resulting in wet beds were frequent and the echo information, such as it was, proved unintelligible.

Two needs were clearly manifest at this time. One was to be able to use contact probing as did the engineers, who were usually looking for flaws in metal structures at a considerable depth—for instance, in a shaft or a structural spar. The other was to be able to photograph the echo signals directly from the cathode ray tube. It was at this point that the association began with Tom Brown, a research engineer in the one-time factory of Kelvin Hughes. His was the real genius which has influenced us to this day. His directors came to visit me in the hospital to find out what I really wanted. They very sportingly voted the sum of £500 to support my researches and I shall always be indebted to Mr Slater, their managing director, for the help which he furnished for years to come thereafter. Meanwhile real teamwork grew up with their research engineers.

Then came a stroke of luck in 1956–7 which changed everything. With the help of our primitive apparatus we were able to establish the diagnosis of a truly enormous ovarian cyst in a woman who at that time was believed to be dying with massive ascites from portal obstruction due to metastatic spread from a radiologically evident carcinoma of the stomach. Haematemesis and weight loss were dominant features. She was so distended that it was quite difficult to examine her but I agreed with the clinical diagnosis of ascites. The ultrasonic screen, however, clearly indicated a posterior cyst wall at great depth instead of the anticipated tangle of echoes from air-containing loops of intestine which one would normally have expected floating up in the central abdomen in ascites. I removed a massive, benign, mucinous cystadenoma and the patient made an uninterrupted recovery. Undoubtedly this encounter saved the woman's life, and the X-ray filling defect in the stomach was, with hindsight, declared to be a radiological artefact. From this point onwards there could be no turning back.

The study of pregnancy began only in 1957, approximately 2 years after we had started.

Two-dimensional display

The diagnostic problems which we were beginning to face were becoming far too difficult to understand with single-dimensional A-scanning, and the need to get into two dimensions became more and more pressing. In this type of display we thus came to use techniques well known in radar sector scanning. The construction of such apparatus could be achieved only in an engineering research department and costs began to mount.

Our first publication did not come until 1958[9]. Our results at that time were crude and our successes infrequent.

Fetal biparietal cephalometry The biparietal diameter of the fetal head is the only one which can be identified with certainty by sonar, but it is also the most important[10]. Willocks exploited the technique further in studying the progressive growth of the fetal skull throughout pregnancy[11]. The method was further greatly refined by Campbell[12] (Fig. 3).

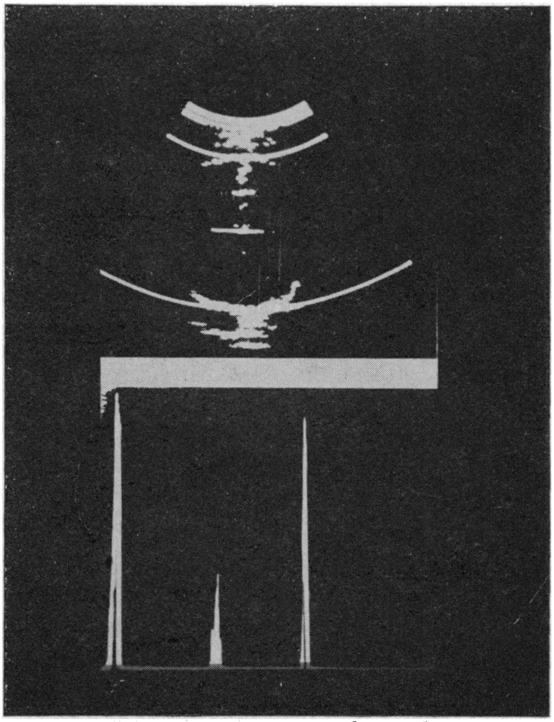

FIG. 3 *Fetal biparietal cephalometry. Upper picture shows a transverse view of fetal skull with electronic cursors (parallel sweep lines applied tangentially to the parietal surfaces, supplying an immediate approximate measurement). Below is a unidimensional A-scan picture identifying the parietal echoes with more clarity and the lesser midline echo between.*

Hydatidiform mole The ultrasonic diagnosis of hydatidiform mole came more or less by chance when it was observed that the mole was visible if the gain (or amplification) of the apparatus was sufficiently sensitive, whereas lowering the gain by 15 dB rendered the mole invisible although the uterine contours were still discernible[13]. This picture distinguished it from artefacts (Fig. 4).

Full bladder technique A chance observation was made in 1963, when a patient who had been kept waiting happened to present for examination with a very full bladder. This had the effect of displacing impenetrable intestine out of the way and providing a clear sounding tank through which to examine the pelvic viscera, including of course the uterus, which was not even enlarged[14].

Our first major success was with a patient who had had a sequence of four spontaneous abortions and who did not even know she was pregnant when we examined her through the full bladder. A curious white ring was seen within the uterus which at first perplexed me until I realized that I was looking at a very early gestation sac[15].

Early pregnancy The study of early pregnancy has over the years become a very big feature of our work[16] (Fig. 5). Its applicability in the differential diagnosis of bleeding in early pregnancy was soon obvious, quite apart from the less common possibility of hydatidiform mole, and it is now possible to arrive at a very ready diagnosis as to whether a uterus contains a continuing pregnancy or whether the case is one of abortion, complete,

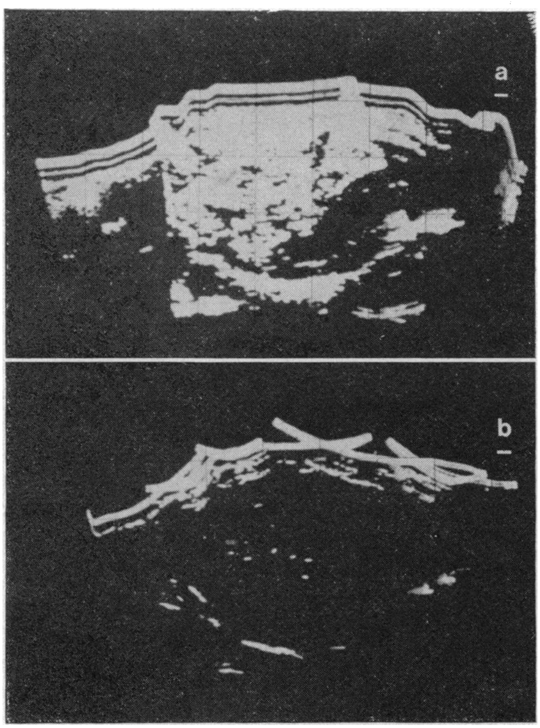

FIG. 4 *Hydatidiform mole. (a) Speckled mass of mole seen at high gain setting. (b) Same view taken at a gain setting of 15 dB less. Speckles have disappeared but posterior wall of uterus can still be seen. High frequency of 5 MHz is used here and helps to prevent confusion with degenerate fibromyoma.*

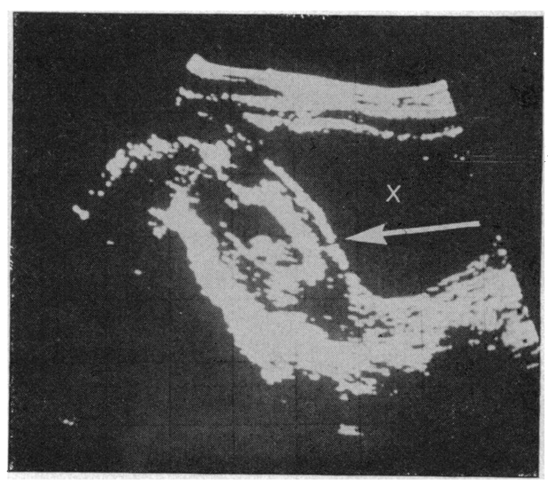

FIG. 5 *Normal pregnancy (9 weeks amenorrhoea) viewed behind full bladder (X). Note gestation sac (arrow) within anteverted uterus. Fetal pole is in lower portion of sac.*

incomplete, or missed[17]. Unless haemorrhage is severe it is now our practice to examine by sonar all cases of supposed retained products of conception, and we curette only those cases in which the uterus is seen not to be empty.

Blighted ovum The recognition of the phenomenon of ovum blighting, which we now believe to be common, has been a natural but more recent development[18], since the gestation sac can be observed from the 5th week of amenorrhoea onwards. This has been reinforced by the display of fetal heart activity or its absence on our cathode ray screens by Robinson[19]. By this technique it is usually possible to detect the fetal heartbeat in a continuing pregnancy by the 7th week of amenorrhoea.

The early recognition of twins is another dividend, and the achievement at Queen Charlotte's Hospital of diagnosing quintuplets at the 9th week of amenorrhoea with apparatus such as ours was a remarkable feat[20].

Placentography Since 1966 sonar has become the method of choice[21, 22] (Fig. 6). All cases of antepartum haemorrhage, and unstable lie are thus examined for placenta praevia, and we consider it a prerequisite for amniocentesis at any stage of pregnancy.

The crash

Just when the winds seemed set fair in 1966 the firm of Smiths, who had been so generously assisting our research, decided to pull out of Scotland and to close their Glasgow Kelvin Hughes factory. Desperately I could see our apparatus suffering the fate of so much electronic apparatus in medicine—namely, the dust-sheet phenomenon.

To my astonishment our Vice-Chancellor, Sir Charles Wilson, instructed me to set up my own department and to engage the necessary engineers—Fleming and Hall of the original research team. Meanwhile the firm of Nuclear Enterprises, not 50 miles away in Edinburgh, took over the medical ultrasonic work. The ranks therefore re-formed and we went on as before.

Range of uses These have multiplied enormously both in gynaecology (Table I) and obstetrics (Tables II and III). Sonar is now an accepted technique in genitourinary surgery and in the study of upper abdominal tumour masses. Ultrasound cardiography has become a subject in its own right and the use of the Doppler shift principle, in the development of which I was not directly concerned, has gained widespread acceptance in studying moving structures, particularly the fetal heart. At the Queen Mother's Hospital, Glasgow, alone more than 4,000 ultrasonic examinations were made in 1972.

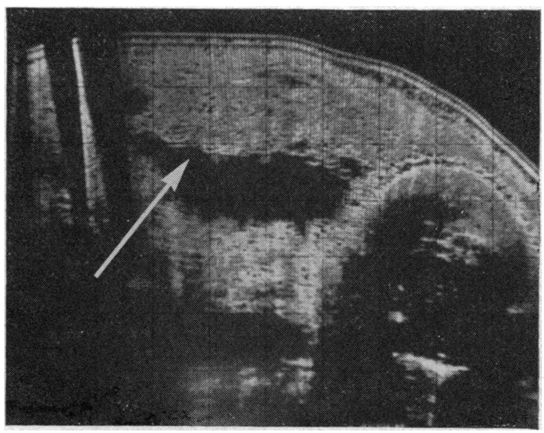

FIG. 6 *Placentography. Demonstrates present grey tone scaling technique. Placenta (arrow) in a case of diabetic pregnancy in 34th week of gestation. Note thickness of placenta and ground-glass, oedematous appearance. At delivery, by Caesarean section, two weeks later, the placenta weighed 1.04 kg. The baby weighed 4.01 kg.*

TABLE I *Gynaecological uses*

Solid and cystic tumours differentiated
Ascites
Differentiation from bowel lesions
Hepatic involvement
Associated genitourinary lesions
Abortion—all varieties
Ectopic pregnancy ±

TABLE II *Obstetric uses (early pregnancy)*

Early gestation—growth
—fetal heart
Blighted ovum
Maturity
Twins
Associated tumours
Hydatidiform mole
Placental localization
Abnormal fetus ±

TABLE III *Obstetric uses (late pregnancy)*

Fetal growth rate (biparietal diameter)
Maturity
Placentography
Twins
Hydramnios
Associated tumours
Previous Caesarean scars
Fetal abnormalities ±
Puerperal complications

Recapitulation

Looking back over the past 18 years and having seen the project more or less from the beginning to its present establishment I can recognize four distinct phases.

I. Disbelief This has been on the whole good-natured. For instance, a distinguished colleague from Edinburgh returned to his city and announced to a hilarious group of students that in Glasgow we used a £10,000 machine to diagnose an ovarian cyst which he could diagnose with a twopenny glove. Our numerous mistakes, which were of course far more instructive than our successes, inevitably added to criticism, which was often well deserved. What has always astonished me is the forbearance of so many of my colleagues.

II. Missed opportunity This was perhaps the most annoying phase, in which colleagues failed to think of sonar at the time.

III. Over-acceptance Here the impossible was expected of us—diagnoses that were far beyond our capacity, limited as we still are to two-dimensional scanning.

IV. Justification There is some irony, though perhaps justice, in the present situation of having to spend the last phase of a rather lengthy experiment in justifying the first part. I refer to such considerations as mounting expense, increasing the complexity of medical science, and above all the question of safety.

Safety

Safety has been uppermost in our minds from the very first and it has been our consistent aim to use the minimum amount of ultrasonic energy and the maximum extent of receiver sensitivity.

Much work had already been done with reassuringly negative results[23,25] when an alarming report of possible chromosome damage appeared from Cape Town in the form of a preliminary communication[26]. We[27,28] and other centres throughout the country, including Edinburgh[29], Cardiff[30] and London[31,32], all with well-established departments of genetics, have failed to confirm this work. Diagnostic sonar uses such minute energy levels that biological effects are almost impossible to measure or determine[33]. Under experimental conditions high-power energy sufficient to produce thermal effects can naturally cause damage. It is possible to concentrate red cells, for example, in certain blood vessels in chick embryos at nodal points within a large standing field of ultrasound[34]. Effects on very early chick embryos exposed at pointblank range with high energies have also occasionally been observed[35], but so far clinical usage of sonar would appear to be safe. The possibility must be faced, however, that there may be safety threshold limits, possibly different for different tissues, but these have yet to be determined. We have therefore to ensure that the future development of more powerful and sophisticated apparatus does not introduce new and as yet unforeseen hazards[36].

The future

The job is not even half done. Our experimental work in three-dimensional display is still at such a primitive stage that it is hardly worth mentioning. More progress is being made in grey tone scaling.

Many workers throughout the world are contributing almost daily to this rapidly growing point of medical knowledge. We can also expect criticism on an increasing scale from those who find medical diagnosis has been made no easier.

I might end by quoting from Robert Browning[37]:

"And the muttering grew to a grumbling;
And the grumbling grew to a mighty rumbling."

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