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The Use of Ultrasonic Reflectoscope for the Continuous Recording of the Movements of Heart Walls.

By

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Introduction.

The effectivity of the pumping action of the heart is essentially dependent on cyclic variations in the volume of the heart chambers and the function of the valves. Increased difference between the diastolic and systolic volume in a heart chamber implies greater amplitude in the movements of the walls. In patients with valvular stenosis or insufficiency the curve for the variation in the volume of heart chambers will deviate from normal (1). Therefore, methods showing the variation in the volume of the heart chambers or the movements of the walls of the heart during the cardiac cycle should be useful in the investigation of cardiac function. Roentgenkymography and electrokymography are methods applied in the investigation of changes in the outline of the heart during the cardiac cycle. RUSHMER *et al.* (2) made continuous measurements of left ventricular dimensions in intact, unanesthetized dogs. The method they used is based on the introduction of a variable inductance gauge in the ventricle, but their method can only be used in animal experiments. In recent years serial angiocardiography with several exposures per second has become an important method for the study of the variation in the volume of the heart chambers during systole and diastole. This method has been used in the clinic, among other things, for the investigation of mitral valvular disease, but it must be performed under anesthesia, it is time-consuming and by no means free of risks.

Many other methods for registering periodic movements caused by the

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heart are under investigation, but only one of these uses ultrasonic sound (3). But that method differs fundamentally from that presented here, since it uses continuous sound waves of 60 kc that pass through the body from the praecordium to the posterior of thorax. On its way, the sound passes the heart and other parts of the body, whereby the sound intensity is decreased by absorption, reflection and refraction. By measuring the sound intensity at the back of thorax it was found that it varied in phase with the heart frequency, but no relation between these intensity variations and the heart volume could be shown.

None of the methods mentioned above give the actual movements of the inner walls of the heart, the knowledge of which would be of importance both for studying the movements of the heart in the body and for clinical diagnosis of heart diseases. It was therefore thought that a technique already well known for some years in industry for the non-destructive testing of materials with respect to flaws might be used (4, 5).

Experimental Method.

The method, known as supersonic reflectoscope, uses short supersonic sound pulses, which are generated by an electrically excited quartz crystal and delivered to the material under investigation. This is done by pressing the disk-shaped quartz crystal directly against the surface of the material under investigation. A good acoustical contact should be secured by using a thin oil film between the quartz and the surface of the material.

If there are any boundaries in the material which are impinged by the sound pulse and which reflect part of the sound back in a direction opposite to its original direction, this reflected sound pulse (echo) will reach the quartz crystal, which then acts as a microphone. If the velocity of the sound in the material under examination is known and constant, the time elapsed between the emission of the sound pulse and the reception of the echo is a measure of the distance between the quartz crystal and the reflecting boundary. This time difference (or distance) can be read directly on a cathode-ray-tube (CRT). This CRT forms part of an apparatus which also contains the electrical equipment for the generation of the electrical signal for the excitation of the quartz crystal, etc. The quartz crystal is connected with this apparatus by a coaxial cable about 3 m. long.

On the left side of the CRT screen, the outgoing sound pulse is represented by a vertical signal 0 (see Fig. 2), while each returning echo pulse shows up as a vertical signal to the right of this outgoing sound pulse. The distance between the outgoing signal and the echo signal along the x-axis on the CRT screen is directly proportional to the distance between the crystal and the reflecting boundary. Further, the height of the echo signal shown on the CRT screen is a measure of the echo intensity.

The apparatus used in the investigations described here was the Ultraschall-Impulsgerät manufactured by the Siemens Reiniger Werke (Erlangen, Germany). In this apparatus the pulse length and intensity could be varied, the pulse length used was usually about $2–5 \times 10^{-6}$ sec., the maximum pulse intensity about $2\ W/cm^2$. The pulse repetition rate was 200 per second. Sound frequencies of 0.5, 1, 2.5 and 5 Mc could be chosen at will.

In nearly all of the experiments described below a frequency of 2.5 Mc was used. When selecting the frequency, different factors have to be observed, the most important of which are the sound absorption in the material under examination and the divergence of the sound beam due to diffraction. Since the absorption of the sound waves increases with increasing sound frequency in both tissue (6, 7, 8) and blood (9), it would be advantageous to use as low a frequency as possible. On the other hand, the necessity of sharp echoes requires both short pulse length and, to reduce diffraction, small wave length of the sound in tissue or blood. With a crystal shaped like a disk, 12 mm. in diameter, as used in these experiments, a frequency of 2.5 Mc was usually found to be the best compromise, except for children below 12 years, when better results were often obtained with 5 Mc.

The apparatus used in these experiments was equipped further with an electronically controlled "lens" device to enlarge and thereby facilitate observation of echo signals on the CRT screen along the x-axis. This device proved to be valuable in the investigations. Finally, a time scale was incorporated in the apparatus, which appeared as a broken line along the x-axis on the CRT screen. This scale could be adjusted so that the breaks in the line between the outgoing and the echo pulse on the CRT screen give the distance directly in centimeters between the quartz crystal and the reflecting boundary for a certain homogeneous medium. In this work the scale was adjusted in such a way that the distances between the quartz crystal and the reflecting boundary could be read directly in centimeters on the CRT screen if the medium between was blood or muscle tissue, the velocity of sound in both being nearly the same.

Preliminary Experiments on Isolated Hearts.

It has been pointed out above that only sound reflecting boundaries can be detected by this method. Thus for the present purpose it was ne-

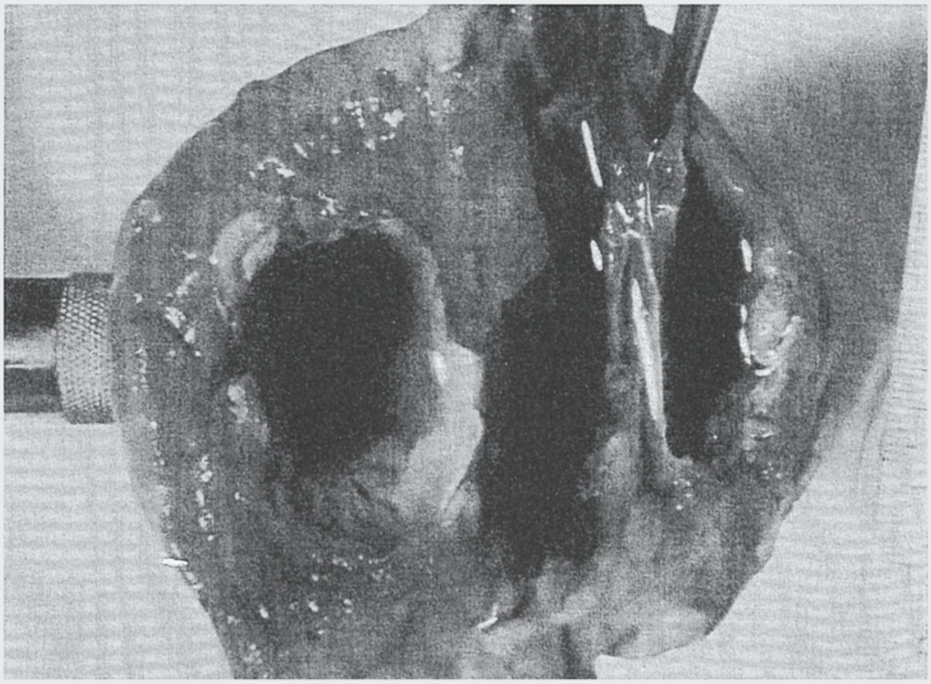


Fig. 1. Quartz — crystal applied to isolated human heart. Crystal frequency 2,5 Mc.

cessary to check that the boundary blood-heart wall fills this condition. This was not to be expected for certain, since the acoustic impedances (10, 11) for blood and muscle tissue are nearly the same. Therefore experiments with isolated hearts were made before starting the investigations on human hearts *in vivo*. The most informative of these experiments is shown by Fig. 1. It shows a human heart from above, which is cut transversely. From left to right we see the left ventricle, the right ventricle and the right atrium. All the chambers are filled with water, and the quartz crystal of the supersonic reflectoscope is applied to the outer heart wall in such a way that the sound beam traverses the heart just under the water surface. The echogram seen on the CRT screen is shown in Fig. 2. According to the figure, many echoes arise, but the co-ordination of the echoes to the different heart walls cannot be seen at a glance. But this is evident at once if both pictures are cut in halves and put together at the line along which the ultrasonic beam is traversing the heart, as is shown by Fig. 3. Each boundary of the type water-heart tissue that is traversed by the sound shows up as an echo signal on the CRT screen, even the thin wall between the right atrium and the right ventricle. The

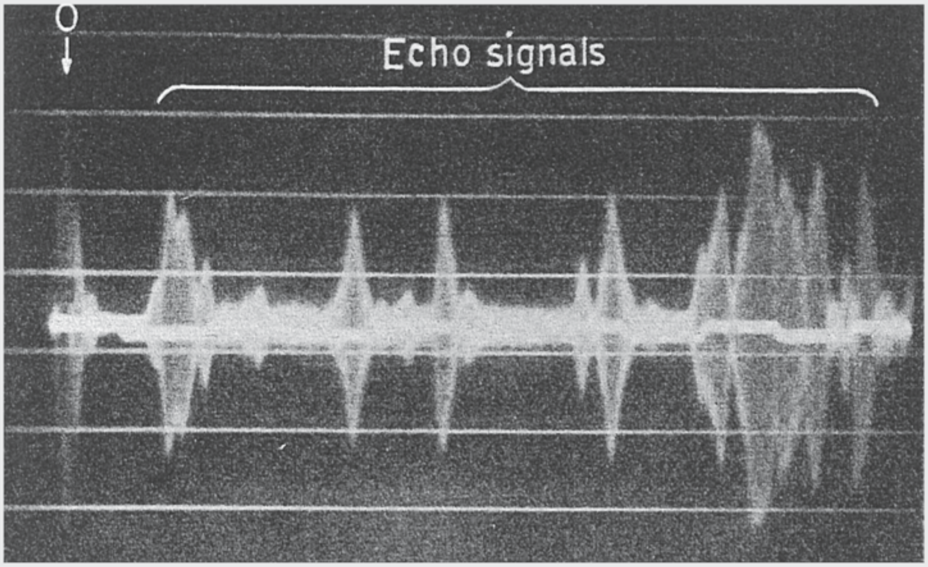


Fig. 2. Echogram obtained on the CRT screen by the arrangement shown in Fig. 1. 0 = outgoing pulse signal.

places at which the heart wall is curved or irregular give rise to diffuse echo signals, since the distance quartz crystal – reflecting boundary at these spots is not constant for different parts of the 12 mm. wide ultrasonic beam. On the other hand, the wall between the right atrium and right ventricle, which has been artificially stretched so as to lie precisely perpendicular to the ultrasonic beam, gives rise to sharp echo signals. The complex echo signal seen at the place where the sound beam, after traversing the heart, strikes the outer heart wall is probably due to the highly convex form of the heart at this place. Naturally, the height and the width of the echo signals vary very much if the direction of the sound beam is changed. The experiments described here were done with water so that the shape of the heart chambers under the water surface can be seen on the photographs. In later experiments the heart chambers were filled with blood instead of water but the results obtained were exactly the same as those found with water.

To check that the co-ordination between the heart walls and the echo signals on the CRT screen given above was correct, the following experiment was performed. An injection needle ca. 0.5 mm. thick was dipped from above into one of the heart chambers shown in Fig. 1 in such a way that it crossed the axis of the ultrasonic beam. This resulted in an additional echo signal on the CRT screen from reflection at the needle.

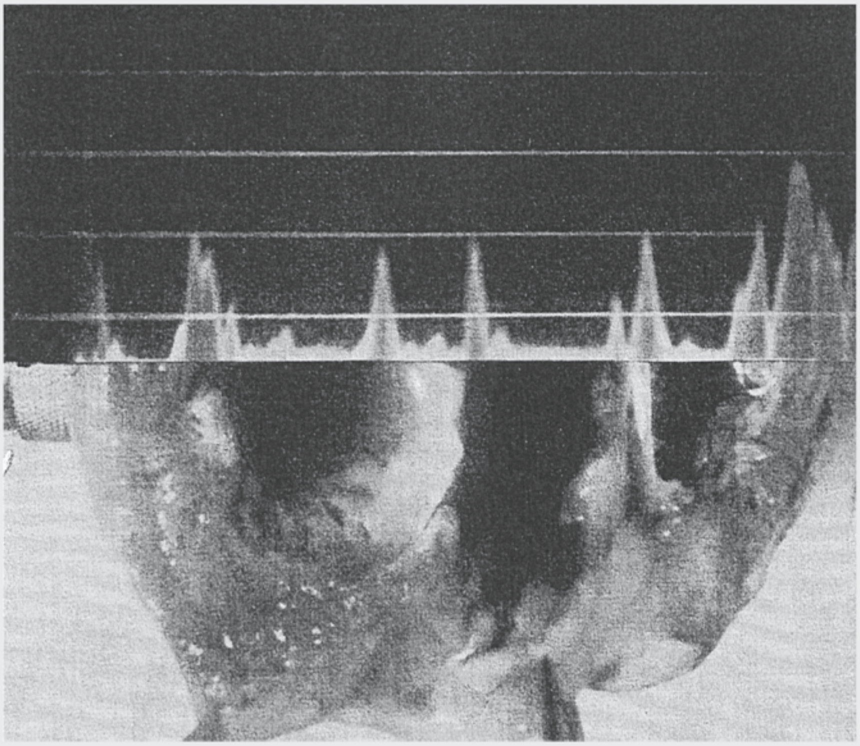


Fig. 3. (For explanation, see text).

The lower half of the Figs. 4 a—c shows the echogram without the needle in one of the heart chambers, as already shown by Fig. 2. In Fig. 4 a the needle was placed in the right atrium and in Fig. 4 b it was placed in the right ventricle and in Fig. 4 c it was placed in the left ventricle. As can be seen from the echograms, the echo signal due to the needle always shows up between the echo signals from the walls of the heart chamber into which the needle was dipped in each case. By moving the needle along the axis of the ultrasonic beam from one wall to the other in the heart chamber, the needle echo signal could be seen moving between the echo signals of the respective walls.

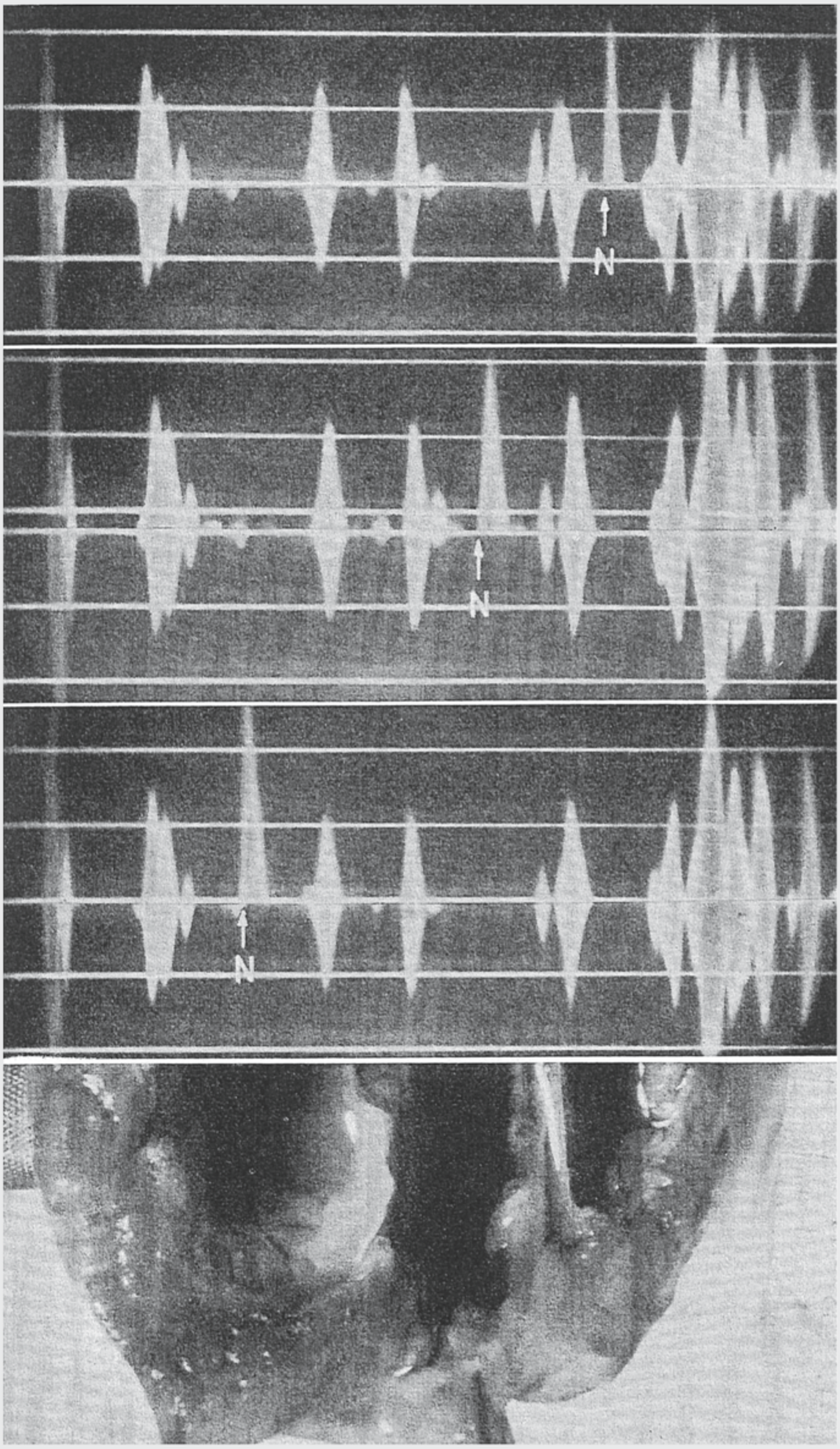
In other experiments, the authors examined echograms from the right atrium of the isolated calf heart. With the aid of a heart catheter passed into the atrium, the volume of the latter was varied, with a resultant corresponding shift of the echo signal from the medial wall of the atrium.

Fig. 4. Needle echo signal (N) appeared on the echogram when the needle was dipped into the right atrium (4 a), right ventricle (4 b) and left ventricle (4 c).

4a

4b

4c



During the experiments it was felt that the reason for the unexpected large reflection coefficient encountered at the inner heart walls were due to the endocardium, since the removal of the latter seemed to diminish the reflection coefficient appreciably. This would be in agreement with the results obtained by J. J. Wild & J. M. Reid (12) with the supersonic reflectoscope on muscle tissue. As yet, no convincing evidence has been produced in support of this assumption.

Short experiments showed, further, that auricular thrombosis may also be located by this method. This should be of interest in the diagnosis of such cases. Even here, more detailed experiments are required.

Experiments on Human Beings.

After the preliminary experiments stated above, an investigation as to the applicability of the supersonic reflectoscope method for the study of the movements of human heart walls *in vivo* was started. In all cases described below a 12 mm. disk shaped quartz crystal was directly applied to the praecordium. Paraffin oil was used to ensure good acoustic contact. The quartz crystal was brought into such a position that the sound beam could pass through an intercostal space and was directed into the heart regions under investigation. A typical echogram obtained on the CRT screen is shown in Fig. 5. It was taken on a patient with enlarged heart. The distance between the outgoing signal 0 and the echo signals along the x-axis on the screen is directly proportional to the distance between the quartz crystal and the reflecting boundaries in the heart. This is true with a fair degree of accuracy, even if the sound passes muscle tissue and blood alternately, since the sound velocities in muscle tissue and blood are nearly the same. Thus, the time scale incorporated in the apparatus was adjusted in such a way that the distance between the outgoing pulse signal and the echo signals could be read directly in centimetres. Each part of the broken line of the time scale seen in Fig. 5 represents 1 cm. sound path in muscle tissue or blood.

There are two reasons for interpreting the echo signals found in this way as echoes resulting from reflections on inner or outer heart walls. The most important is that the echo signals on the CRT screen oscillate both along the x-axis and in their magnitude with the frequency of the heart under investigation. This is very convenient for the correct interpretation of echo signals arising on the CRT screen. Since the experiments on the isolated heart shown above prove that reflections can occur at the

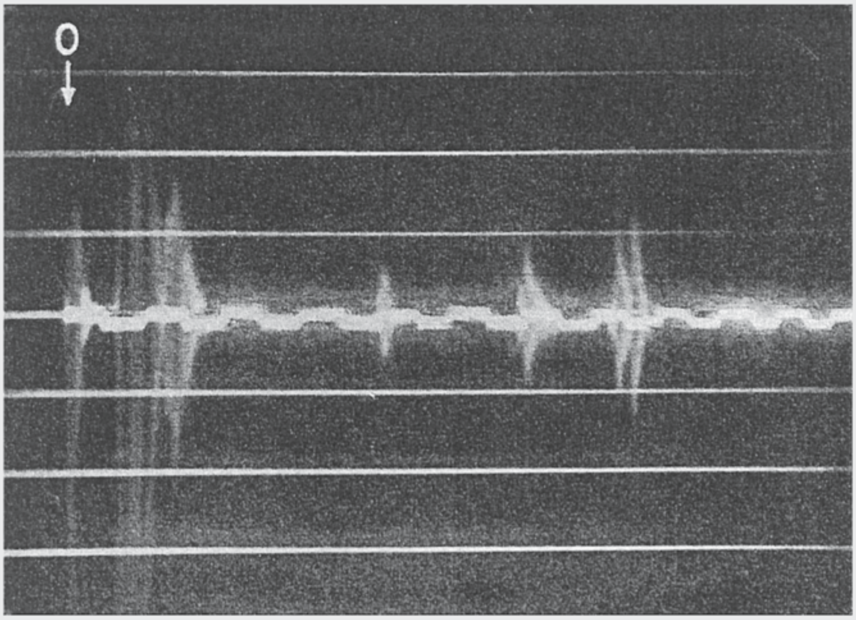


Fig. 5. Echogram obtained on the CRT-screen when quartz crystal was applied to the praecordium of a patient with cardiac enlargement.

boundary blood — heart tissue, this assumption is not contradicted. Further, no such echo signals can be found when the crystal is placed elsewhere on the thorax of a person except on the praecordium. This is due to the large absorption coefficient of the aerated lung tissue for high frequency sound.

On account of this large absorption of high frequency sound in lung tissue and pronounced reflection in skeletal parts (13), the sound beam should be delivered in such a manner as to avoid these media as far as possible. It was found that, when the quartz crystal was placed against the skin of the praecordium and in the intercostal space and when the ultrasonic beam was directed against the heart, one or more echoes ranging from 4 cm. to 11 cm. were recorded in persons with a heart of normal size. The echo signals were best obtained when the crystal was placed in the left I: 4 and I: 3. In the investigation of apparently normal adults, the ultrasonic beam is directed in sagittal direction from the left I: 4 adjacent the sternal border, whereby the posterior echo signal was recorded at a distance of 9–11 cm. from the outgoing pulse signal. If the heart is enlarged, this posterior reflecting surface will lie at greater distance from the anterior wall of the chest. Table 1 shows the relationship between

Table 1.

	Distance in centimeters of the echo signals from the outgoing signal.	Distance in centimeters from the anterior thoracic wall to the posterior of the heart, as measured on the roentgen film.	Total heart volume in millilitres.
E. L.	16	17	2440
A. L.	9,7	10,5	
B. N.	8,8	9,5	510
M. L.	12	13	
E. B.	11,3	13	1185
G. M.	12,2	13,5	1090

the distance to the posterior wall, as measured by the echo signal, and the distance from the anterior thoracic wall to the posterior part of the heart shadow, as measured by the roentgen film at the same level, in persons with varying heart volume. It is in this plane which passes through the left sternal border that the sagittal diameter of the heart is greatest, for which reason the distance measured on the roentgen film corresponds to the plane passed by the ultrasonic beam. It is apparent from the table that the posterior echo signal lies within the structure of the heart and thus represents a partition in the heart. The difference between the distance to this partition and the distance to the posterior part of the heart shadow corresponds to the thickness of the posterior wall of the heart and therefore the echo signal may correspond to the inner surface of this wall.

If the sound passes a rib, the results obtained are less accurate, and sometimes no reflection is obtained from the heart walls. If the crystal is placed against the chest outside the praecordium and where the sound waves will meet lung tissue as soon as the thoracic wall has been passed, no echo from the heart walls will be obtained. As mentioned above, this was expected.

In patients with cardiac enlargement, reflections are obtained over the major part of the praecordium which is explained by the fact that the lung tissue between the wall of the chest and the heart has been pushed aside. On the other hand, patients with emphysema and those of pyknic body build have more lung tissue between the anterior wall of the chest and the heart, which explains that it is much more difficult to obtain satisfactory echo signals in such persons.

Continuous Recording of the Echo Signals.

Since mere visual observation of the motion of the echo signals seen on the CRT screen does not yield much more information than the

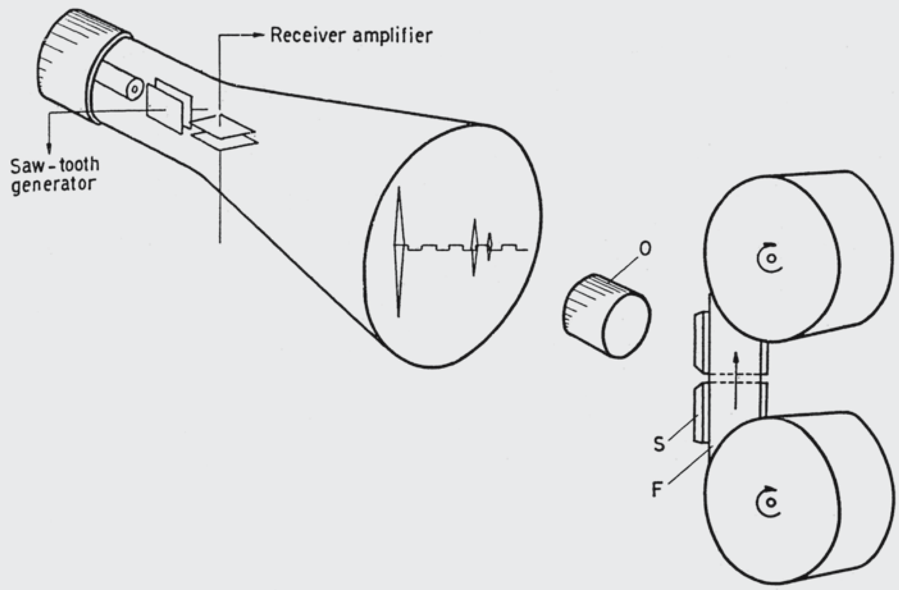


Fig. 6. Apparatus for recording UCG-curves.

distance of the reflecting heart walls from the crystal surface, a continuous photographic recording of this motion was required. To this end a horizontal slit S (see Fig. 6) was mounted in the image plane of the camera objective 0, otherwise used for photographing the CRT screen, the slit width being 0.5 mm. Directly behind this slit, a 24 mm. Ilford HP3 film F was continuously moved at right angles to the slit at a rate of 1 cm/sec. The slit should be placed parallel to, but a little above, the image of the x-axis of the CRT, so that no light coming from the x-axis and the time scale visible on the CRT screen reaches the film. If no echo signal appears on the CRT screen, nothing will be marked on the film except the outgoing pulse signal which will be recorded as a straight line parallel to the direction in which the film is moved. If a constant, non-pulsating echo signal appears on the screen, even this will produce a straight line on the film parallel to the outgoing pulse line. The distance between these two lines is then proportional to the distance crystal-reflecting boundary. If the echo signal pulsates along the x-axis (which is the case in these investigations) a curve will be recorded on the film. The distance of this curve to the outgoing pulse line will correspond at any moment to the distance crystal-reflecting boundary. In this way, the variations of the distance crystal-reflecting boundary can be recorded with respect to time.

Because of the relatively large slit width relative to the film velocity, the resolving power of the present apparatus is not too good. Using higher

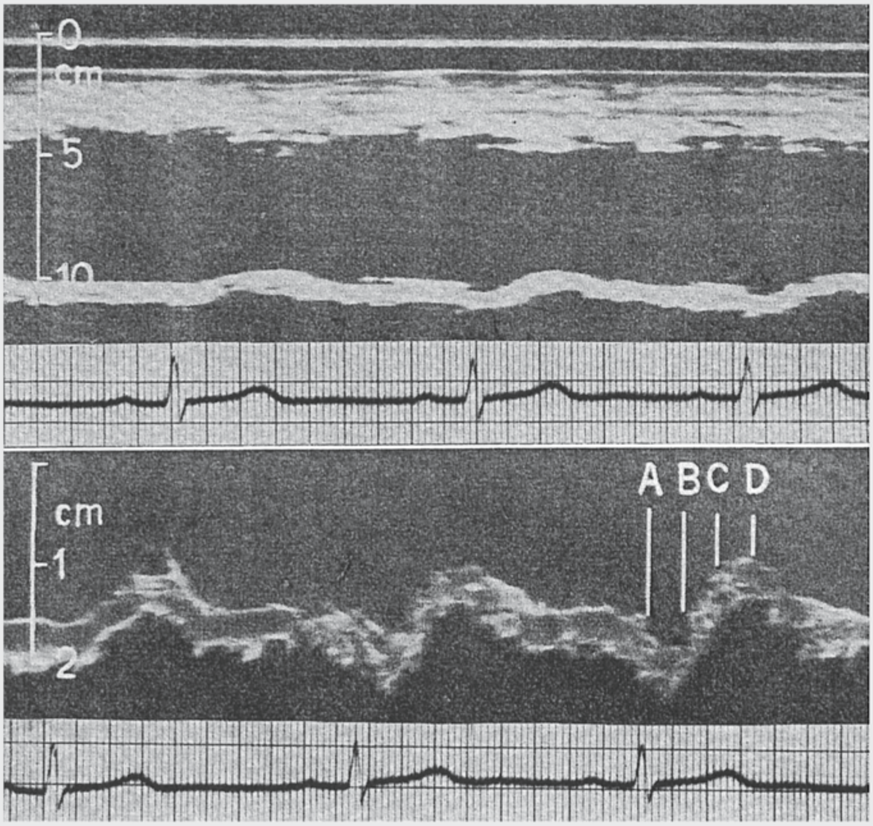


Fig. 7. Top: General view. Bottom: Enlargement of the movements of the posterior wall of the heart. A—B indicates the isometric contraction when the wall moves 2—3 mm. in dorsal direction. B—C denotes the first part of the emptying phase, maximum ejection, when the wall rapidly moves in ventral direction. C—D denotes the final phase of emptying, reduced ejection, when the wall moves slowly in ventral direction.

light intensities on the CRT screen, it will be possible without much difficulty to increase the resolving power to the same degree as is achieved in commercial ECG apparatus.

Typical curves obtained in this way from heart walls are shown in Fig. 7 to Fig. 11. Since the method uses supersonic sound to gain information about the function of the heart, in the following these curves will be referred to as UCG (Ultrasonic Cardiogram). In the lower figures the electronically controlled "lens" device mentioned above has been used. In these cases the movements of the echo signals are magnified about 4 times, whereby a more detailed study of these movements is possible. Using the scale given on the side of each figure, the actual size of the movements

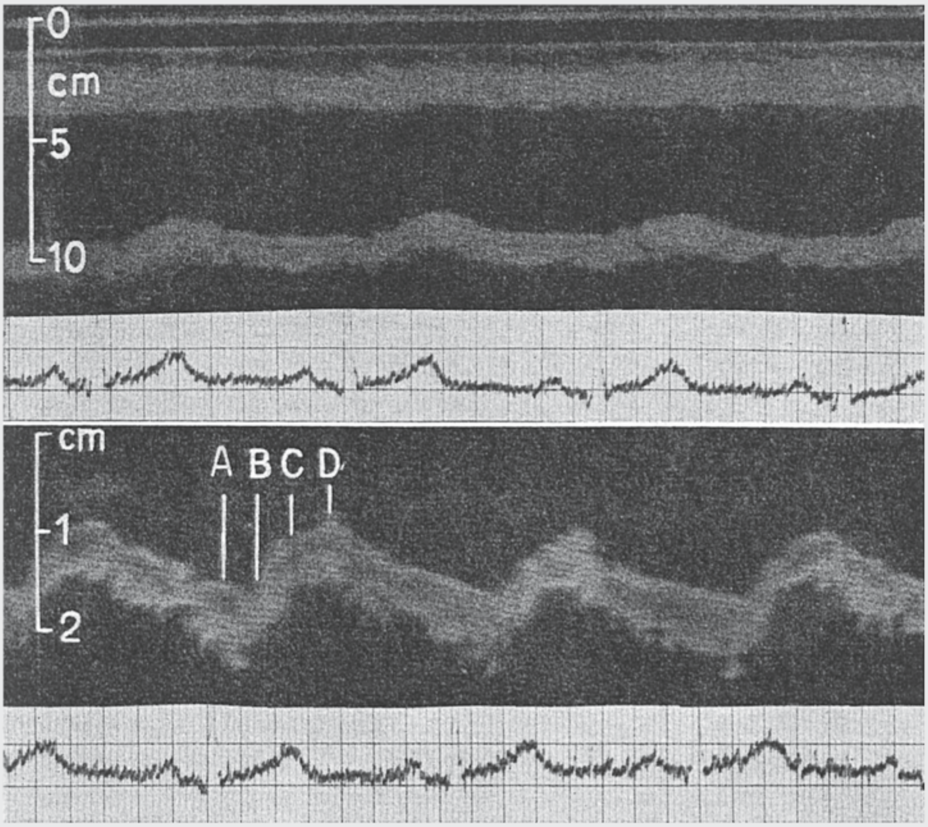


Fig. 8. UCG from a normal case. Top: General view. Bottom: Enlargement of the movements of the posterior wall of the heart.

of the heart wall under observation can be measured directly. The film velocity is the same both for the normal and for the enlarged recordings.

As can be seen from the figures, the echo signal width on the CRT screen also varies periodically. There are two reasons for this behaviour. If the reflecting boundary is not a plane or is not placed exactly at right angles to the sound beam, the echo signal will broaden, since the distance crystal-reflecting boundary is different at different places on the crystal surface. Further, in the apparatus used in these experiments, not even an echo signal reflected from an ideal plane placed at right angles to the beam direction will show up as a thin vertical line on the CRT screen, but more like an isosceles triangle with a very narrow base along the x-axis. This base width increases with the strength of the returning echo signal. Thus the base width of the echo signal pulse on the CRT screen increases with the height of the pulse, thereby making both the base width and the

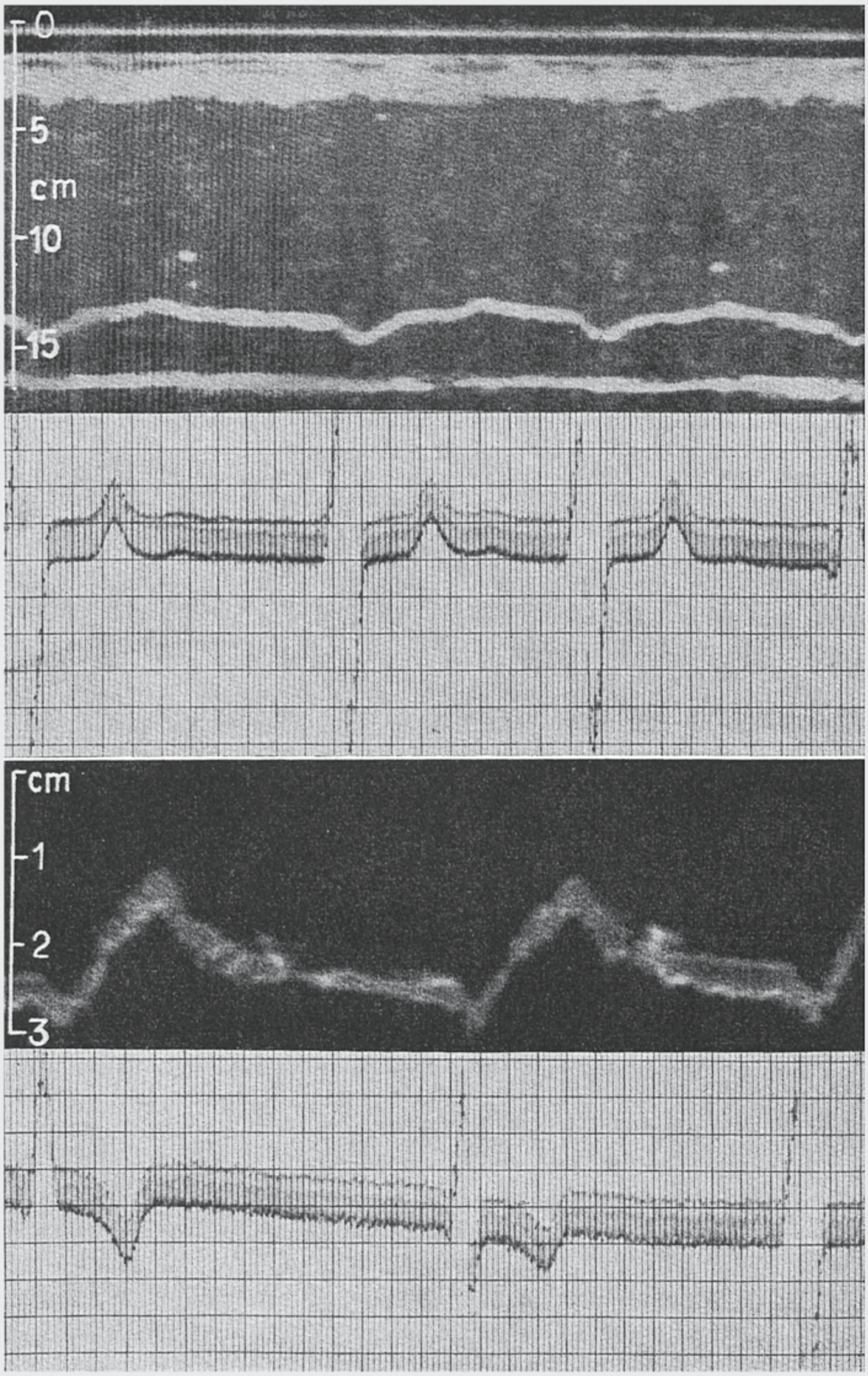


Fig. 9. UCG from a patient with aortic regurgitation. Top: General view. Bottom: Enlargement of the movements of the posterior wall of the heart.

height of the echo signal a measure of the strength of the reflected sound pulse. Thus the cause of a broad track in the UCG's may have been that the reflecting boundary was curved or not situated at right angles to the sound beam or that the echo signal was very strong. A thin track indicates a sharp but faint echo.

Since it was felt that the information about the movements of different parts of the heart gained by this method would be much easier to interpret if a simultaneous recorded and synchronized ECG were available, a synchronization device was applied to the UCG and ECG apparatus. After developing the 24 mm. UCG-film, the negative was enlarged just so much that the synchronization marks on the UCG film and ECG paper coincided. In this way a synchronization of UCG and ECG was achieved.

Preliminary Results.

The factors influencing the distance crystal-reflecting boundary are respiratory excursions of the chest and the movements of the heart. The influence of respiratory movements in the experiments hitherto performed appear to be of minor importance, so that it was not necessary for the patient to hold his breath during the examination. The movements of the heart during the cardiac cycle are complex. They are determined partly by the movements of the individual walls in association with the variation in the volume of the respective heart chambers and, second, by movements of the heart as a whole. The latter movements are due to changes in the shape of the heart during isometric contraction and relaxation.

Figs. 7 and 8 show curves for two normal persons. The crystal was placed in the left I: 4 immediately lateral to the sternal border and the ultrasonic waves were delivered in sagittal direction. The maximum distance to the reflecting wall of the heart was 10.0 respectively 9.3 cm. The curves thus represent the dorsal part of the heart. In the enlargement of Fig. 7 the various phases of the movements occurring during the cardiac cycle are marked.

Fig. 9 shows the curve tor tne posterior wall of the left ventricle in a patient with aortic regurgitation and hypertrophy of the left ventricle. The curve deviates from normal by showing much greater amplitude during ejection systole and a much more abrupt return in dorsal direction during the beginning of diastole. This latter movement coincides in time with the rapid regurgitation in the beginning of diastole in advanced aortic insufficiency (1).

UCG's taken from the left I: 3 about 3–5 cm. lateral to the sternal border over the region of the left atrium showed very rapid movements

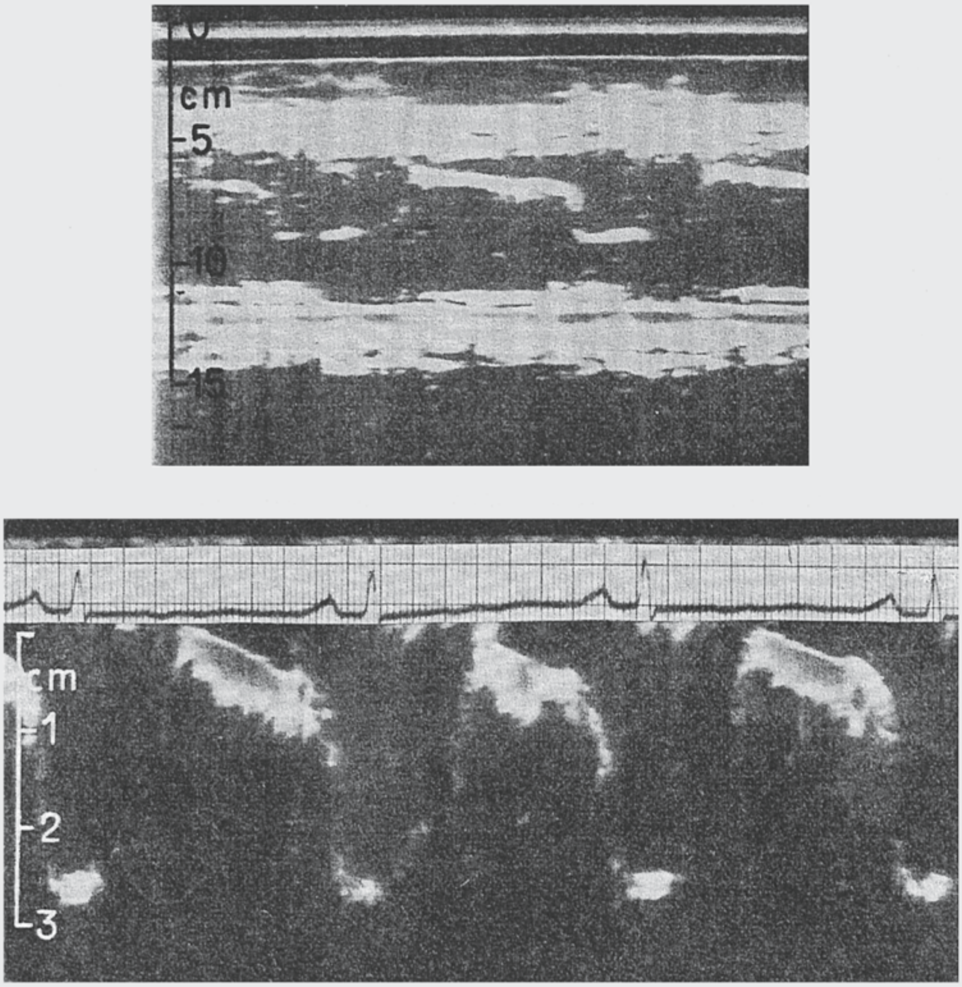


Fig. 10. UCG-curve showing the movements of left auricular wall in a case of mitral stenosis. Top: The curve shows a reflecting surface about almost 6 cm. from the anterior thoracic wall in the beginning of diastole. Bottom: Enlargement of the reflecting surface. From the beginning of ventricular diastole, when the atrio-ventricular valves open, the reflecting surface moves 6–7 mm. in dorsal direction. Immediately after the beginning of the P-wave in the electrocardiogram the sound reflecting surface makes a rapid movement in dorsal direction. This movement has an amplitud of about 2 cm. During ventricular systole the wall returns to its original position.

at a depht of 5–7 cm. in some cases. In normals such movements were recorded only as fragmentary curves. All of them, however, showed a rapid movement of about 1 cm. in dorsal direction at the time of atrial systole, for which reason the relationship with atrial activity is obvious. For this reason, these sequences were studied in some patients with mitral

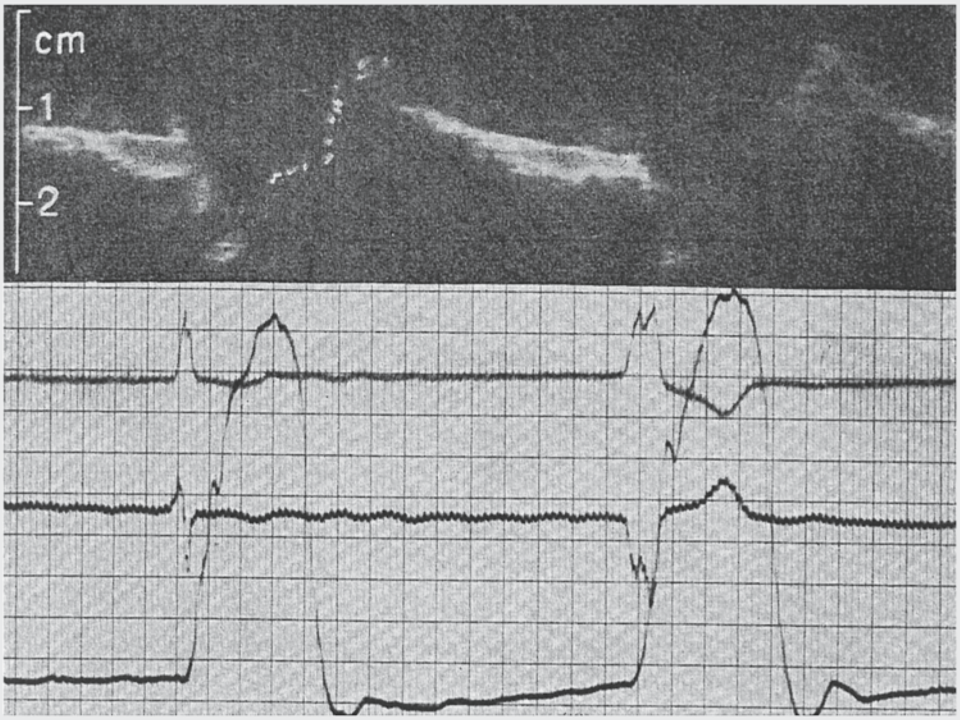


Fig. 11. UCG-curve showing the movements of left auricular wall in a case of mitral stenosis with auricular fibrillation. As in fig. 10, there is a gradual movement in dorsal direction after opening of the atrio-ventricular valves. A rapid movement is recorded at the time of the isometric contraction of the ventricle. At the time of the isometric relaxation of the ventricle, the reflecting surface returned in ventral direction.

valvular disease and enlarged left atrium. Better curves then were obtained from the left I: 3. Fig. 10 shows a curve for a patient with pure mitral stenosis. Valvulotomy had been done before and post-operatively there were no signs of mitral regurgitation. The curve lies at a depth corresponding to the position of the anterior wall of the left atrium, and shows at the time of the atrial systole a rapid movement in dorsal direction. In cases of mitral stenosis with auricular fibrillation, in which effective mechanical contraction of the atrium is absent, this movement is missing (Fig. 11). In both cases, the wall during the first part of ventricular diastole is gradually displaced in dorsal direction. Fig. 11 shows a retraction of the wall during ventricular systole, which corresponds to the systolic collapse seen in pressure curves from the left atrium and which is due to the pull exerted by ventricular contraction.

The echosignals obtained from left I: 3 over the region of the auricle correspond thus in position to the anterior wall of the left atrium. The movements of the echosignals correspond to the variation in the volume of the left atrium and to the contractions and displacements caused by the ventricular activity.

Summary.

1) It has been shown that it is possible to locate blood-heart wall boundaries by the supersonic reflectoscope method using frequencies of about 2.5 Mc.

2) The method was applied for the locating of heart walls on living human beings and continuous registration of movements of the heart walls was found possible.

3) Recordings are shown of the movements of the left ventricle wall in the normal and in the diseased heart. Further, movements of the left atrial wall in mitral stenosis were recorded.

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