THE ULTRASONIC VISUALIZATION OF SOFT TISSUE STRUCTURES IN THE HUMAN BODY

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I think most of you are aware of the fact that ultrasonic techniques are currently being used in three principal areas in medicine; namely, for its destructive action in the central nervous system and in therapy of tumors,[1] in physical medicine especially for the treatment of arthritis,[1] and in diagnostic visualiazation of body structures, particularly those soft tissue structures where current diagnostic techniques are not of optimum value. This paper will be limited to a discussion of the diagnostic use of ultrasonic techniques. Our particular equipment works with power, only a fraction of that used for therapy and much less than that used in the field of physical medicine. For this reason the problem of damage to tissues has not been encountered in our work. The observers working with this equipment and the test animals used in this work have shown no evidence of any tissue damage. Usually intense pain precedes induction of tissue damage with ultrasonic waves. There has been no pain or other evidence of tissue damage in the use of our techniques.

Several other groups have worked on this general problem[1,2,3,4,5,] but we will limit the present discussion to our own experience.[6,7] Perhaps a series of questions and their answers will best explain what we are trying to accomplish with this method.

Supported in part by a grant from the Veterans Administration and in part by a Grant No. C-2423 NSS from the U. S. Public Health Service.

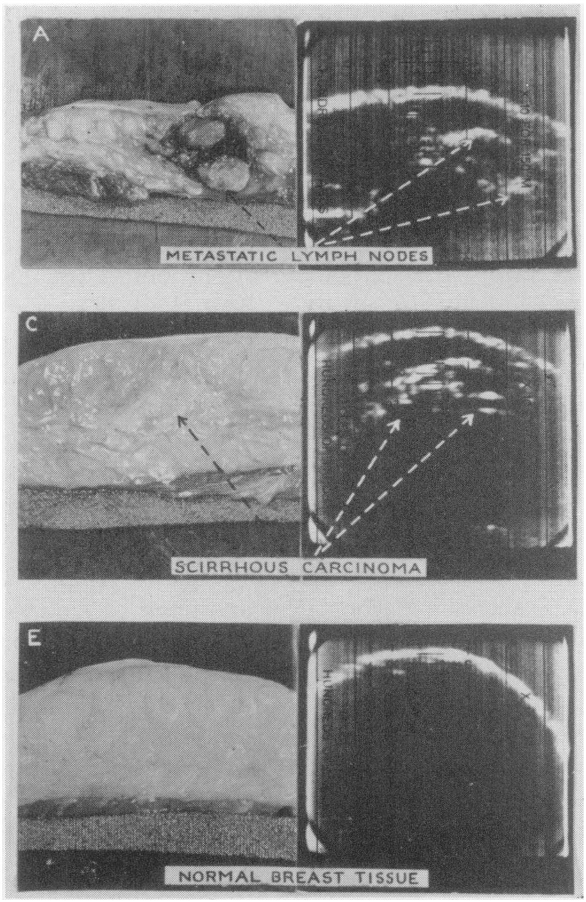

FIG. 1. The middle picture shows a pathological specimen of a breast with scirrhous carcinoma.

The upper picture shows metastatic lymph nodes from the same specimen.

The lower picture shows a non-carcinomatous area of the same breast. The corresponding somagrams for each specimen are shown. It will be noted that the areas of carcinoma show up as white patches inside the general outline of the breast.

What does ultrasonics technique offer that cannot be obtained with current diagnostic methods? Figure 1 (middle picture) shows a pathological specimen of a breast with scirrhous carcinoma which was not palpable prior to surgery. The somagram, or picture, taken with our equipment is shown beside it. There is the outline of the skin surface of the specimen, and then a series of contrasting areas are shown at the level where the carcinoma was identified by the pathological sections. The remainder of the breast tissue casts no particular shadow. In an area where there is no carcinoma, as shown in the lower picture (Figure 1), no shadows are noted on the somagram. In the upper specimen containing the metastatic lymph nodes, definite shadows appear in an area corresponding to the site of the lymph nodes containing the carcinomatous lesion. Thus, it can be seen that areas of different tissue density such as carcinoma will show up on the somagram.

How is this visualization accomplished? Figure 2, in the lower part, shows a pathological specimen of a kidney cyst. The upper part of this figure shows how the somagram of this kidney cyst appeared on the somascope screen. There is the large outline of the cyst wall and then the homogenous area inside the cyst wall which corresponds to the clear cyst fluid found when the specimen was sectioned. The outline of the kidney is seen adjacent to the cyst, and some of the structures inside the kidney, especially the central portion are visualized.

The general method by which visualization is accomplished closely parallels the echo ranging techniques which are used in sonar and radar. In essence, we are using the electronic techniques of radar as applied to the field of ultrasonics.

A trigger generator (timing mechanism) causes the pulse generator to develop a simple square wave pulse of approximately 0.25 microseconds duration, which is controllable from zero to 3000 volts amplitude. This pulse is passed to an ultrasonic crystal which is mounted in a waterproof housing and which under the influence of the pulse voltage, is caused to expand and contract violently for a short period of time, thus producing a mechanical wave. By using ultrasonic

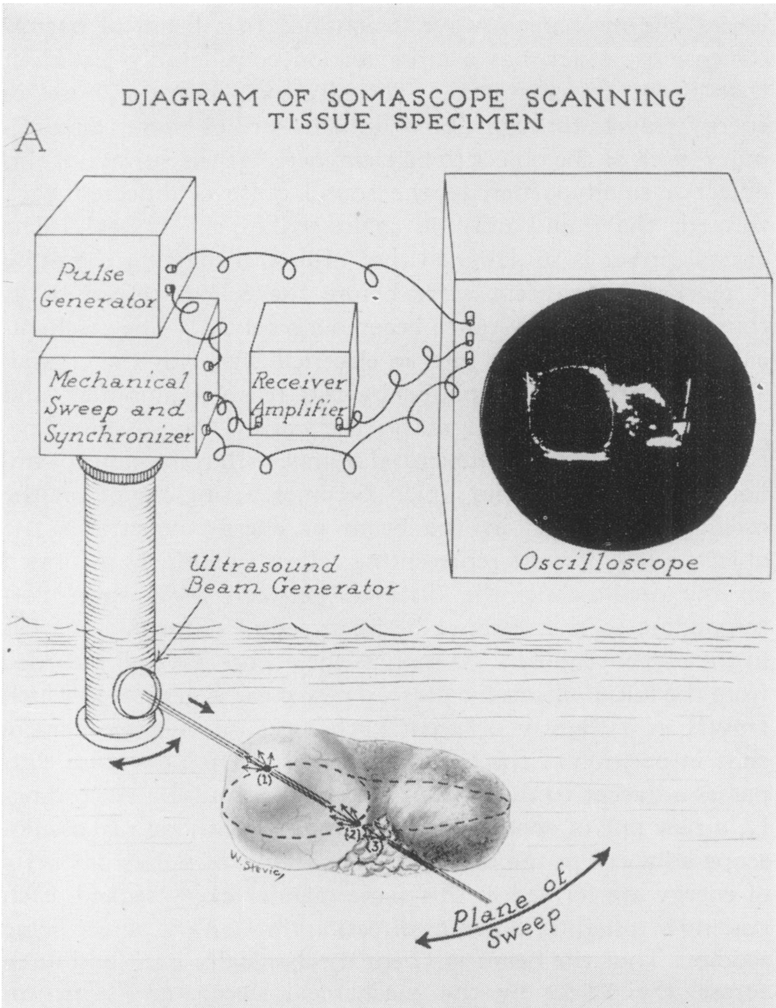

FIG. 2. Shows the major units of the somascope and the manner in which the kidney cyst depicted in the lower part of the diagram appears on the somascope screen.

lenses, the mechanical wave is confined to a beam of narrow dimensions, which has a cross section considerably less than that of the driver crystal. The ultrasonic beam or burst of energy travels through liquid until it strikes some discontinuity, such as the object to be examined. At the surface of this object a small portion of the sound pulse is reflected back through the liquid until it again strikes the crystal. The crystal driver is so designed that after transmitting the pulse it reaches a quiescent state before the echoes return to it, thus allowing the crystal to become a receiver. The mechanical echo is transformed into an electrical signal by the crystal. This signal is then amplified by the receiver amplifier, and presented as a single spot on the cathod ray oscilloscope. Each discontinuity of structural change within the object similarly produces an echo which becomes a single spot on the oscilloscope. Thus, as the beam of energy penetrates the object, a line of spots representing reflective surfaces is formed on the oscilloscope, the distance between these spots corresponding to the distance between sound reflecting surfaces in the object studied. As soon as the echoes have all returned from the initial ultrasonic pulse, a new pulse is generated which travels in a slightly different path, because of a mechanical shift in position of the sound generator. The new pulse thus passes adjacent to the path of the previous pulse. Accordingly, a new line of spots is produced on the cathode ray oscilloscope adjacent to the old line. Thousands of pulses or bursts of energy are formed in this same manner every second, each passing in a slightly different direction through the object being studies. Thus the beam is swept mechanically back and forth across the object by the mechanical sweep and synchronizer while single pulses draw lines of spots on the screen. Due to the rapidity of this operation it is possible to form a visually continuous picture on the oscilloscope screen in a manner which is very similar to that employed in television. It should be noted that by this operation the somascope produces only a cross sectional picture, much as would be produced if the specimen were sectioned with a knife and the resultant slice seen from above.

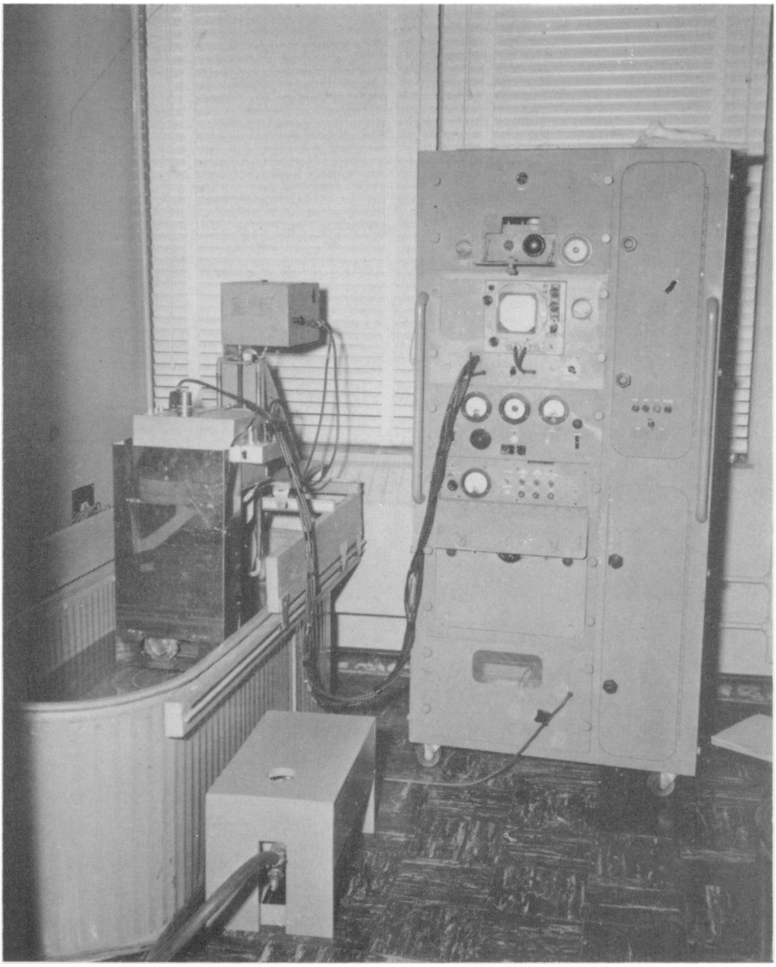

FIG. 3. A picture of the somascope in its present form.

Ultrasonic mechanical waves in the megacycle region will not pass through air without prohibitive losses; therefore, the subject or specimen to be examined must be either submerged in a liquid media or be in direct contact with some solid material through which the sound can travel. In our work, the anatomical structure being studied is submerged in a water-filled tank.

The somascope is in the physical form shown in Figure 3. The power supplies, pulse generator, amplifiers, synchronizing systems, and oscilloscope are housed in the large steel cabinet. The mechanical scanning system and sound generator are mounted on the large tub. The patient is placed in the tub which is filled with warm water and the sound head is moved into position for study. The somagrams or sound pictures appear on the white square (face of the oscilloscope) seen in the upper portion of the steel cabinet. The picture formed may be interpreted directly by the observer as in the case of a fluoroscopic examination, or for permanent recording photographed with a standard camera. All somagrams are studied carefully on the screen frequently from different angles before the final picture is taken, thus, it is possible for the observer to identify structures which might seem difficult to identify in the pictures being presented to you.

How well can this equipment differentiate between structures of different density which are closely approximated? Figure 4 shows a cross section of the neck of a normal person taken at the level of the fifth cervical vertebra. The general surface of the neck can be seen and within this one can locate the skin, trachea, carotid artery, jugular vein, and most of the muscles by their surrounding fascia. The neck represents one of the most difficult areas in the body to study since the structures are closely approximated and hence somewhat difficult to separate and identify. This identification is easier when the structure is moving as in the case of an artery. In the lower part of the figure can be seen the wave motion of an artery, and the A, C and V waves of one of the deep veins. The first pictures show the reflected wave motion to the skin over the carotid artery. If one were to adopt to our equipment the "moving target" technique of radar which has been well worked out for spotting of planes or determining the speed of a car on the highway, then one might study in greater detail the wave motion of the heart and great vessels. Thus, it might be possible in the future to determine the size of the

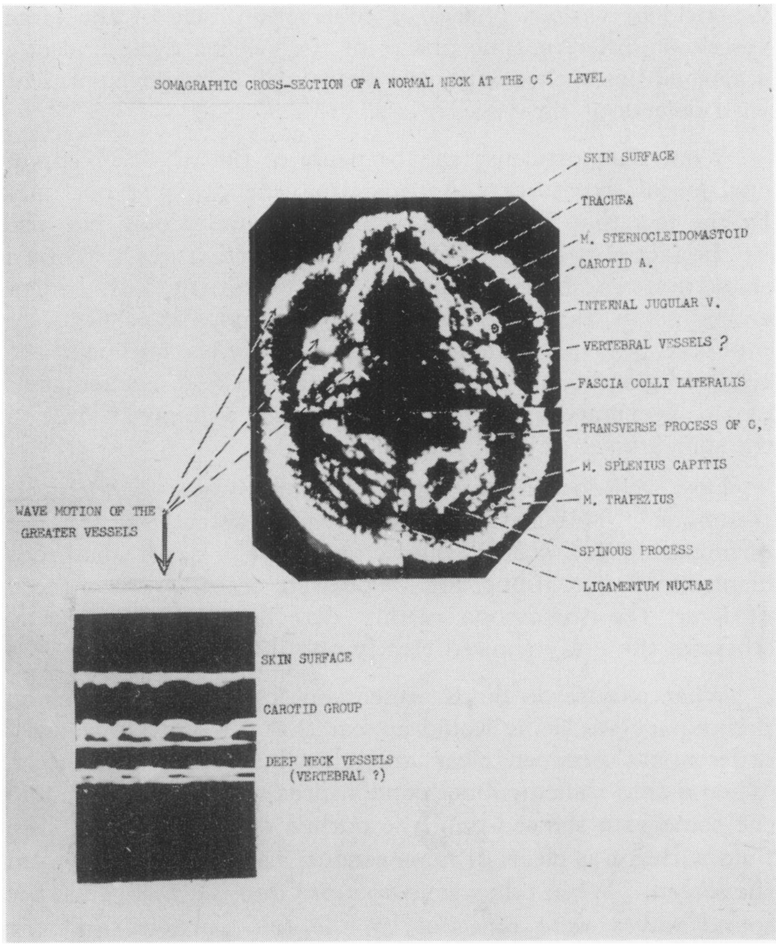

FIG. 4. Shows a cross section of the neck of a normal person taken at the level of the 5th cervical vertebra.

In the lower left hand corner can be seen the somagram of the wave motions of the skin over the carotid artery of the carotid artery, and of one of the deep cervical veins.

ventricle in various phases of contraction, size of the large vessels at different time phases of the cardiac cycle and any abnormalities in the contractile phase such as might be present with defects of the vessel walls.

What diagnostic use can be made of the displacement of anatomical structures? A tumor may be detected not only by the fact that it abnormally reflects sound waves, but also by the fact that it may displace adjacent structures. When a somagram was taken of the neck of a patient with benign colloid goiter, the gland was quite homogenous so echoes were produced principally at its surface, and only the outline of the enlarged gland could be seen. If there had been adenomas or cystic degeneration, then these areas might well have shown on the somagram.

How well does a non-metallic foreign body show with this technique? This instrument can readily detect the presence of foreign bodies, such as plastic or rubber. When small rods of metal, plastic, rubber and wood were embedded in a piece of liver, the somascope readily detected all four objects; whereas, the x-ray showed clearly only the metal rod.

What picture do fluids present on the somagram? From preliminary studies it would appear that the somascope could differentiate between clear and cloudy fluids in the body. When a thin walled rubber condom was filled with clear fluid the somagram showed only the outline of the condom. The fluid within was clear, or homogenous, and cast no shadow on the screen. When talc was introduced into the fluid, then the sound waves were reflected by the talc particles and the previous hemogenous appearance of the fluid had changed to approximate the appearance of a "snow storm".

What other areas in the body can be visualized by this tecnhique? The liver and spleen are good subjects for partial examination by our current equipment. Figure 5 (first picture) shows a somagram of the abdomen of a normal person. The outline of the right half of the rectus muscle and other layers of the abdominal wall are easily identified. The bowel peristalsis and the progress of food through segments

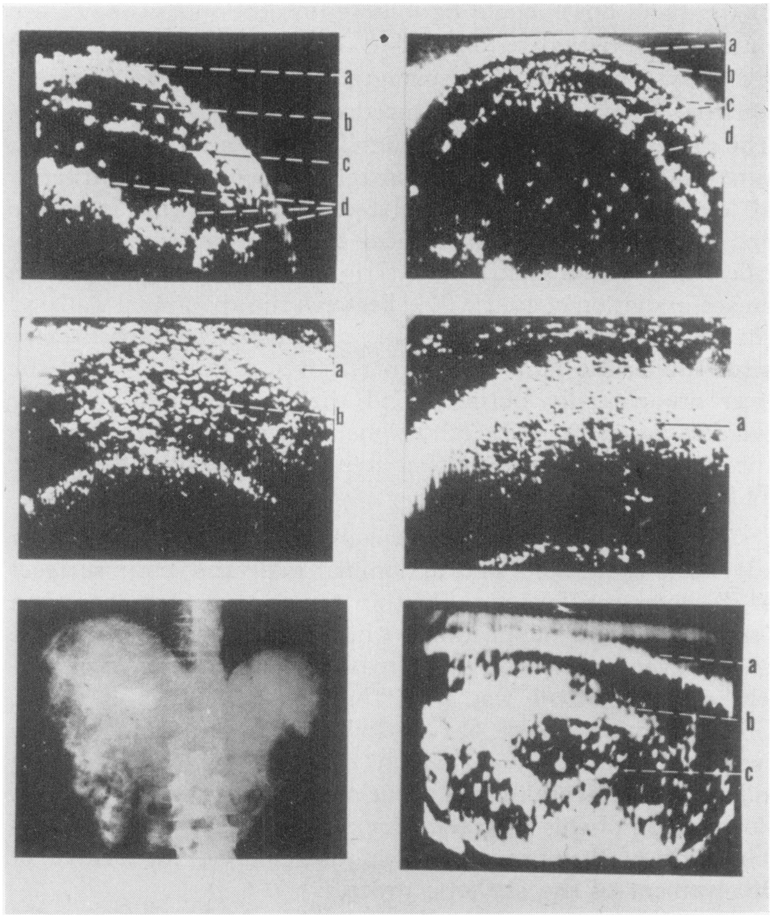

FIG. 5. Shows a series of somagrams taken over the liver area of the abdomen. The first is of a normal individual as food is passing down the intestinal tract. The second is of a patient with moderately advanced cirrhosis with hepatomegaly. The third is of a patient with far advanced cirrhosis where one can note the "snow storm" like appearance of the liver. The fourth is of a patient with diffuse miliary melanoma of the liver. The fifth is a thorium dioxide radiograph of a patient with nodular metastases in the liver. The sixth picture is the corresponding somagram of the same patient.

of the small bowel could be followed on the somascope screen much as the barium is followed in the fluoroscopic examination by x-ray. The adjacent somagram in Figure 5 is that of a patient with moderately advanced cirrhosis and hepatomegaly. The patient had a marked accumulation of ascitic fluid at the time of examination. The somagram shows a thin anterior abdominal wall which correlated with the thin atrophic abdominal wall seen on physical examination. Immediately below this is seen a dark clear strip which probably represents an accumulation of ascitic fluid between the abdominal wall and the anterior liver surface. This dark strip was not present after the ascitic fluid had been removed. Both lobes of the liver are partially outlined and the anterior and posterior surfaces are seen. Few echo signals are returned from within the liver, thus suggesting that it is relatively homogenous at all levels.

The next somagram was taken from a patient with far advanced cirrhosis. The abdominal wall and both surfaces of the liver can be seen. Within the liver outline there is a "snowstorm like" appearance which was obtained at all the power levels considered to be reasonable. Autopsy examination of this patient was done three weeks after this study. Gross examination of the pathological specimen showed a typical "hobnail" liver, which on cross-sectioning showed miliary foci of dense fibrous tissue and areas of hepatic necrosis. Comparison of this with the previous figure suggests that this might be of diagnostic value in determining the degree of involvement of the cirrhotic process.

A somewhat similar picture to that of the above patient was obtained from a young man who had had a malignant melanoma removed from the back of the neck eighteen months prior to examination. At the time of examination he had cutaneous metastases and a marked hepatic enlargement which suggested liver metastases. The somagram in Figure 5 shows the same "snowstorm like" appearance which was seen in the previous case. No discreet areas of tumor metastases can be seen. One month later at autopsy, the cut liver surface presented a dense, black, stippled appearance dg to diffuse miiary metastatic malignant melanoma. There were no discrete areas of metastatic nodules.

The next patient studied had a carcinoma of the thyroid which had been proved by surgery and radio-iodine uptake studies. In the thorium dioxide radiograph (5th picture, Figure 5) the liver was found to be markedly enlarged and showed definite nodular metastases. In the somagram powerful echoes were obtained of a more localized nature than was obtained in any of the previous liver examinations. On the somascope screen many of these areas had the appearance of being roughly circular in shape and seemed to correspond to the radiographic findings. This is shown in the 6th picture, Figure 5.

What are some of the problems which must be solved before this instrument will be clinically useful in the average physicians' hands? It should be remembered that all pictures presented represent cross-sections of the anatomical areas studied. Most physicians are accustomed to seeing anatomical structures in three dimensions and are not familiar with the cross-sectional presentation. In studying a tumor of moderate size, it may be necessary to make as many as 48 cross sectional pictures before the exact size and outline of the tumor can be shown. Recently we have developed a 3 dimensional technique which will also permit stereoscopic viewing of the tissues studied. This is accomplished electronically so that sequential cross sectional pictures are partially superimposed to achieve a three dimensional form. The projection of view can be changed electronically from 0 to 90°. In the upper pictures, Figure 6, we utilized as a test object, a small box made of wire which contains a small wire in the center running from one edge at the top to the opposite edge at the bottom of the box. When two views are separated by about 10 degrees then it is possible to view the object stereoscopically. The lower part of the figure shows the results of this technique as applied to visualization of the normal forearm. One can note the 3 dimensional projection of the skin surface and some of the fascial structures.

Another current problem is the inability to visualize structures immediately behind a strong reflecting surface, particular-

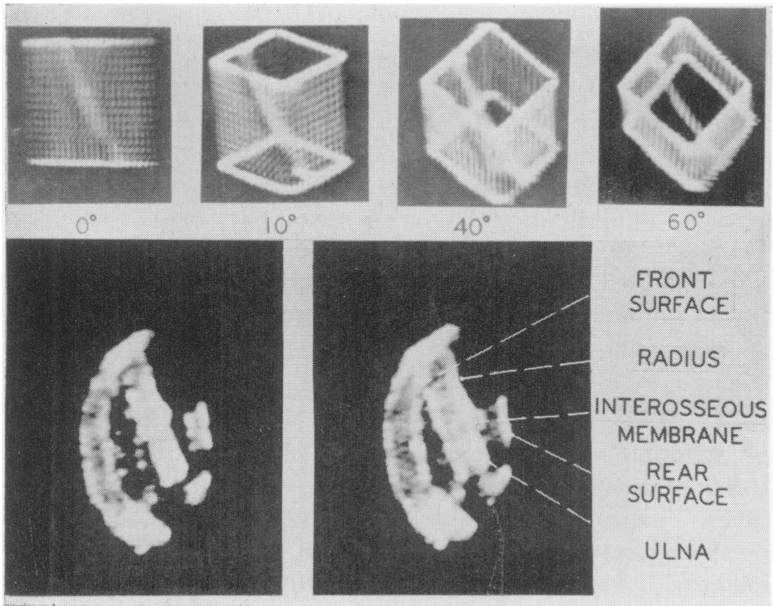

FIG. 6. Shows projection at several different angles of a small wire box. The lower picture represents a three dimensional view of a section of the forearm of a normal person.

ly dense tissues such as bone. This problem was solved in the somagram of the neck (Fig. 4) by obtaining a combination of four pictures with the scanning device placed in four different quadrants. Had the scanning head been placed only in one position, then the anatomical structures lying behind the vertebrae and trachea would not have been visualized. This problem is currently being solved by devising a scanning system which will move all the way around the test object, thus making it possible for example to visualize the entire neck in a single picture.

One of our most important problems at present is the improvement of definition. Currently, we have a definition of approximately 16 lines per inch. We would be able to obtain ideal definition if we could obtain definition up to approximately 32 lines per inch. Various types of picture artifacts have proved troublesome in this work and have been partially eliminated. By constructing a gain compensator we have corrected for the absorption of sound in tissue in such a way that objects on the surface of the body appear on the screen as of the same size and density as those deep within the structures. Sound waves traveling circuitous pathways are eliminated by altering the time of pulsing of the crystal so that only those waves directly reflected by a structure are recorded on the screen continuously.

What areas cannot be studied by this equipment at the present time.? Many body areas have not yet been explored. With the present equipment it is still not feasible to study an organ such as the pancreas because of the many structures overlying it. The skull presents a quite difficult problem since the ultrasonic wave cannot readily penetrate the bone without an extreme loss of amplitude. Dr. Ballentine and Dr. Hueter have been studying the ultrasonic visualization of the brain structures using a different approach, but have not yet found a solution to this particular aspect of the problem.[8]

What might such equipment promise to do for medicine in a diagnostic manner in the future? Certainly one can speculate about the use of this equipment in many different fields, and those of you with special interests will think of something which has not yet come to our mind. One might well be able to visualize the interior structures of the heart and to define such anatomical entities as the size of the ventricular wall, the valve structure, papillary muscles, the septum, etc. One can certainly locate non-metalic foreign bodies which are not readily apparent by external examination. One might well define the limits of an area of injury in the deep soft tissue structures which followed trauma. Certainly one would hope to define accurately such structures as the kidney, pancreas, liver and spleen. These represent structures where current diagnostic methods are limited. Fat is a good reflector of sound waves, and fortunately many of these organs are surrounded by a layer of fat which makes it much easier to define their general structure by the somascope. The ability to define the extent of a metastatic lesion might prove of great value to the surgeon, especially if we could also define structures such as nerve and artery which enter the tumor tissue.

When will such an instrument be available for clinical use, and what will it look like? You may well have gathered from the previous discussion that we are devoting all our efforts to improve the equipment, especially its definition and ability to penetrate to deeper structures. Another essential improvement is some method which will obviate the use of a tub of water since this presents many problems in the examination of sick patients. It should be possible to pass the sound waves into the tissues by means of a probe consisting of a fluid-filled, thin walled rubber bag located between crystal and skin.[4,5] It will be necessary by clinical experience to define the limitations and abilities of this particular instrument. For example, no attempt has been made at present to use contrast media, but one might well expect that an injection of .9 per cent saline would serve as a simple contrast medium, could readily be absorbed by the tissues after examination, and would not present the hazards of the present radio-opague materials necessary for x-ray examination. The completed unit would probably be about the size of a large television set and its operation no more difficult than the usual x-ray equipment. The cost of such equipment would certainly be a guess at this time, but several manufacturers have suggested that it would run somewhere in the neighborhood of $10,000.00 to $15,000.00. A new unit which was recently constructed for our own work cost in the neighborhood of $18,000.00.*

SUMMARY

We have described the operation of new diagnostic equipment which we have called the somascope and which utilizes the principals of sonar and radar to visualize soft tissue structures in the body. The pictures are presented on an oscil-

*Partially constructed by Denver Research Institute, University of Denver.

loscope screen, and their presentation can be watched much as on a fluoroscopic examination, or photographs can be made with an ordinary camera for permanent preservation of records. Examples of the visualization of such pathological lesions as breast cancer, kidney cyst and cirrhosis or metastatic malignancy of the liver have been presented. The ability of this instrument to visualize small and closely approximated structures such as nerve, artery and vein have been shown in a somagram of the neck. The future of this instrument has been discussed, including the necessary developments before it becomes a clinically useful tool, what it may offer to medicine from a diagnostic standpoint, and what the final equipment may look like and cost.

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DISCUSSION

DR. FRANCIS D. W. LUKENS (Philadelphia): One of the areas that is very difficult to examine is the pancreas. Will this machine outline a normal pancreas?

DR. ELLIOT V. NEWMAN (Nashville): I would like to ask if defects in the heart such as are found in congenital heart disease may be detected by this method.

Also, it would be of interest to know how much such an instrument costs, since it may become useful clinically.

DR. FRANCIS C. WOOD (Philadelphia): As I remember it, Dr. George Ludwig, about the time the war was on, got interested in using something of this sort to detect gallstones. He found out he couldn't do it because of the air-fluid interspaces in the abdomen. Do such interspaces interfere with the function of your instrument? Secondly, I think he and some others worked on a method of visualizing the ventricles of the brain without putting air into them. Have you tried to do this?

DR. RICHARD FRANCE (Nashville): Can you tell us whether calcium will show up?

DR. HOLMES (Closing): We have been primarily interested in developing these techniques to a point where it will be practical for other individuals besides ourselves to use and, therefore, have not explored all the possible uses for this equipment.

Now for the first question of Dr. Lukens with respect to the pancreas, that is one organ which we have made no attempt to visualize on the somascope. The spleen and the liver we have visualized successfully, but the pancreas lying behind other structures will be a more difficult problem.

With respect to the heart, I don't think there will be any question, Dr. Newman, that we will be able to determine such things as the size of the heart wall and probably to visualize defects in the septum, papillary muscle, and perhaps, even the valves. The problem is essentially one of adapting the present equipment to take advantages of the motion of the heart by utilizing the well developed "moving target" techniques of radar and sonar. Since this instrument is putting out several thousand pulses per second, it will be possible by integrating it with the EKG to study a particular phase of the cardiac cycle. While these techniques will take time to set up, they present no particular technical difficulties.

As far as cost goes, RCA has been very interested in this apparatus and have been trying to estimate the probable commercial cost of such equipment. They have been surveying the medical electronics field and have ranked this as an interesting and important development. Anyone can guess, but suggested figures have been $10,000.00 to $15,000 when produced commercially. The instrument I showed you on the slide cost $18,000.00 to build, but this figure can probably be cut when it is produced on a commercial basis.

As for gallstones we have done no complete study of this area, but we all feel that we will be able to visualize gallstones, particularly those not visualized readily by x-ray. We have tried particularly to study structures that we know the x-ray would not show easily.

I would like to re-emphasize that something like plastic foreign bodies is going to be very easy for this particular instrument to visualize, but the brain will be quite difficult because of the extreme loss of amplitude in passing these waves through the skull.

We are also receiving requests to apply this technique to non-medical uses. For example, in the case of jet fuel and rockets, their effectiveness depends on how well the tank or cartridge is packed, and equipment of this type might well be used to determine the efficiency of packing. Where x-ray is used to detect flaws in steel, this might well be used for the same purposes in plastics and other non-metals. The Colorado Veterinary School feels that this equipment might be used in judging cattle, particularly with respect to the magnitude of the fat layer under the skin, and even the degree of "marbling" in the muscle. Every few days another possible use for this equipment is presented to us.