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Ultrasonic Visualization System Employing New Scanning and Presentation Methods*

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New methods for the ultrasonic visualization of tissue, achieved by employing a newly developed versatile instrumentation system, are outlined and their application to the examination of brain is illustrated. The complete system, whose operating characteristics are described in detail, incorporates an on-line medium-sized digital computer, implementing omnidirectional scanning, utilizing three translational and two rotational degrees of freedom; relief display, which combines intensity modulation and deflection of the oscillograph beam by the echo signals; and segmental construction of echograms, which incorporates wide dynamic range combined with high resolution via program control of receiver gain as a function of range and echo strength. Omnidirectional scanning permits the more complete viewing of tissue interfaces than is possible with the usual compound-scanning methods. Relief display provides an additional parameter as compared to the common flat format for the presentation of echo information in a two-dimensional picture, and the type of echo signal composition at individual positions on an echogram thus can be represented The relief format also facilitates detection of significant echo signals against the background. Comprehensive presentation eliminates the need for, and problems associated with, time-variable gain in receiver amplification and also provides for much greater flexibility in the choice of an amplifier gain characteristic as a function of signal amplitude. The illustrative results presented demonstrate that new ultrasonic visualization methods can be used to detect and localize (1) internal structural features of the cranial vault, (2) external features of the brain (ventricular, cisternal, and fissural surfaces); and (3) major blood vessels (midsagittal sinuses) in considerable detail, under the condition that acoustic energy does not traverse bone.

INTRODUCTION

PROBLEMS associated with the detection and localization of structural features of anatomically normal and abnormal human brains by ultrasonic echo methods are receiving increasing attention. The relatively simple method (*A*-scan presentation) by which the entire information on the screen at any time corresponds to the echoes received for a single position of the axis of the examining train of acoustic pulses has been applied by a number of investigators to detect lateral shifting of midsagittal structures,[1–18] and it is used

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almost routinely in some clinical centers. The accuracy of the method has been studied by a number of investigators, in particular, extensively by White and collaborators.[12,15,17] Although the technique does have some diagnostic value in clinical practice, for example, to indicate major shifts of midsagittal structures in patients with cerebral tumors or vascular disorders, it is becoming increasingly evident that more sophisticated approaches are necessary if even a moderate amount of information is to be obtained on the positions of intracranial structures.

A number of investigators[19–26] have become concerned with developing compound-scanning methods combined with two-dimensional representations of the echoes from planar sections through the brain and surrounding structure (*B*-scan presentation). These two-dimensional ultrasonic pictures are in the most general case constructed from the echo information obtained in response to examining pulses corresponding to a number of angular orientations and spatial positions of the axis of the examining pulse train. Compound scanning is employed with the common transceiver arrangement in order to detect a reasonable fraction of the "area" of the tissue interfaces within the cranium, since the strength of the intercepted echo from a site is markedly dependent on the angle between the direction of propagation of the incident acoustic radiation and the normal to the tissue interface at the site. Many tissue boundaries constitute reasonably good specular reflectors (angle of incidence equal to angle of reflection), so it is not possible to build good cross-sectional pictures by attempting to view acoustically such interfaces by employing either a single or a narrow range of angular orientations of the incident radiation. In general, it is not feasible to offset the reduction in the ratio of the received-to-transmitted signal on deviating more than a few degrees from the configuration wherein the angle of incidence is equal to the angle of reflection by increasing the sensitivity of the detecting system (background noise appears) or by increasing the intensity level of the transmitted pulses (echoes for which specular conditions exist on detection are so large by comparison that neighboring nonspecular ones cannot be resolved). Of course, in addition, the level of the transmitted pulses cannot be increased indefinitely because damage to the tissue ultimately results. Another observation, pertinent to employing a wide range of angular orientations of the axis of an examining transceiver with respect to the configuration of the tissue interfaces to be detected, is the desirability of being able to interpret the relative strengths of received signals (for optimum viewing of each site) as a measure of the magnitude of the gradients in the values of the acoustic parameters—characteristic impedance and sound velocity—of the tissues at partially reflecting interfaces.

This paper is concerned with the description of an ultrasonic visualization system that incorporates new scanning and presentation methods and other techniques. It also includes, as an illustration of its use, some typical results that have been obtained from the examination of brain. A comprehensive presentation of the ultrasonic visualization of intracranial anatomy is the subject of a separate paper.[27] One methodological advance, designated *omnidirectional scanning*, provides for viewing interfaces within planar cross sections of the tissue by examining pulses incident on these interfaces not only for a range of angular orientations of the axis of the examining beam within the plane of section (*B* scanning), but also with the axis at a variety of angular orientations with respect to the plane of section. The information for the presentation is obtained in this case by time gating of the incoming echoes so that only those corresponding to an appropriate range interval are recorded for each position of the transducer

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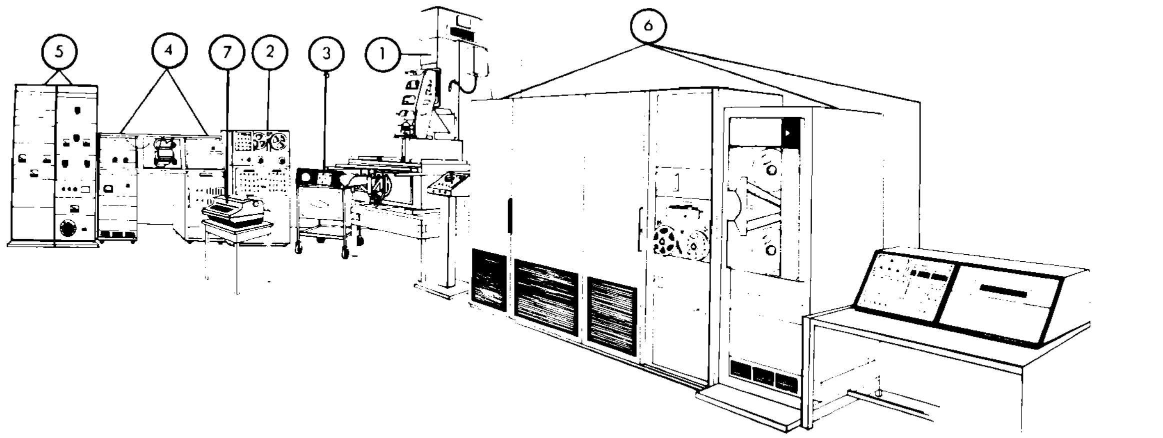

FIG. 1. Major components of ultrasonic visualization facility illustrating physical arrangement. (1) Apparatus for positioning and moving acoustic scanning assemblies and associated equipment—basic unit is a modified turret drill, Cintimatic model DE. Attached to the base are a sound tank containing the transmitting liquid in which the acoustic scanning assembly moves and an apparatus that supports the head of the animal and aligns it with the axes of the scanning motions. (2) Electronic control unit, Cincinnati Acramatic 330. This unit places the positioning apparatus (1) under tape control and therefore serves as an interface between it and the computer (6). (3) Reflectoscope—Sperry model UM721. This equipment is used during various acoustic alignment procedures as well as "on line" as part of the video channel for the system. (4) Console housing: visual display instrumentation, digital timers, digital-to-analogue converter units, and power supplies. (5) Driver for providing radio-frequency power to any of a variety of acoustic transducers. (6) Digital computer—Raytheon 520. This instrument is used on-line to control scanning motions and positions, amplifier gains, echo signal processing, video display, and time sequences of events in general. (7) Typewriter for data input (FORTRAN language) and print-out from the computer.

assembly. Of course, the maximum width of the range interval that can be employed in any case is a function of the angle that the axis of the examining beam makes with the planar slab of tissue under examination. For example, when the axis is in the plane of the slab, no time gating need be employed to ensure that the received echoes arise from structures in the slab (the range interval is limited in this case to maintain azimuthal resolution); but when the examining beam axis is normal to the slab, the time gating must be adjusted so that the range interval corresponds to the slab thickness. The two-dimensional presentation is thus constructed, in general, from a series of mutually abutting strips. The considerable increase in the elaboration of scanning outlined here provides more complete information on the loci of tissue interfaces that normally partially reflect incident sound than can be achieved by the usual compound-scanning configurations. In a second methodological innovation, *relief display*, the echo information is presented in a two-dimensional format but with a relief effect, i.e., the echo patterns have the appearance of mountain ranges and peaks illuminated from the side, stronger echoes corresponding to taller peaks with broader bases. This type of presentation, as contrasted with the usual *flat* format, makes it possible to distinguish between different types of echo compositions at single sites on the echograms and thus constitutes a means of presenting more structural information. It also facilitates the identification of significant small signals against background noise, and it seems to aid the viewer in assimilating echogram-pattern information. A third innovation, the use of an on-line digital computer in the instrumentation, not only implements the new methodological advances just indicated, but it also provides for increasingly sophisticated processing of echo signal data, e.g., maintaining wide dynamic range without concomitant loss of resolution, and it essentially eliminates the need for time-variable gain. In addition, a general-purpose computer greatly reduces the need for designing and developing a series of expensive special-purpose equipment items during that evolutionary phase of a program, in which accumulating data generates a continuing demand for major changes in the instrumentation.

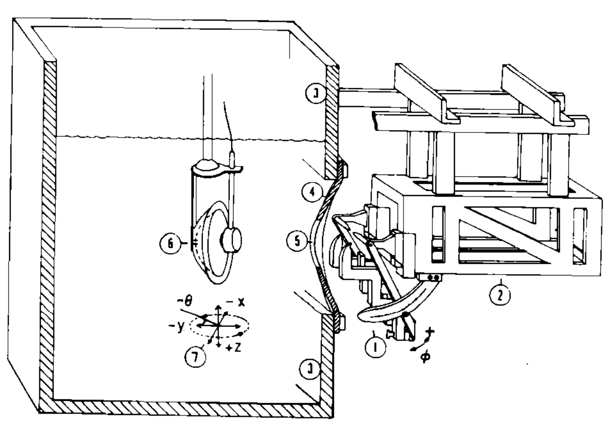

FIG. 2. Arrangement of modified Clarke head-fixation apparatus, sound tank, and examining transducer assembly. (1) Head-fixation apparatus— double arrow designates rotational degree of freedom about earbar axis. (2) Supporting framework for head-fixation apparatus. (3) Sound tank. (4) Water-barrier annular diaphragm. (5) Aperture in diaphragm that is closed in use by dorsal part of subject's head (6) Examining ultrasonic transducer. (7) Triorthogonal motion and single rotational degree of freedom of the examining transducer.

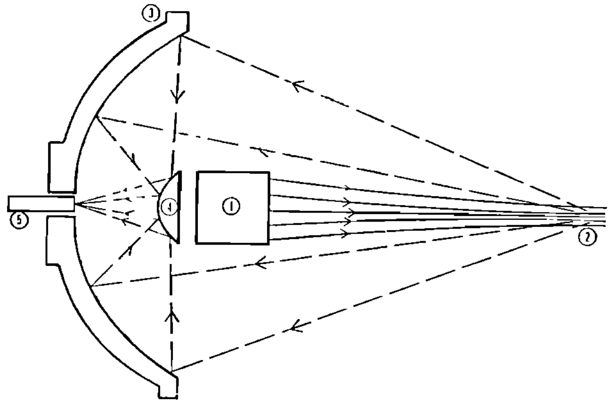

FIG. 3. Configuration of ultrasonic examining transducer assembly. Arrows show the direction of sound propagation from the source unit (1) to the pickup microphone (5). (1) Ultrasonic source transducer incorporating 3.0-MHz PZT 1 in. diam plate with planoconcave lens for some collimation (Automation Industries style 57A2412). (2) Focal region of the system—region in which best resolution is achieved. (3) Ellipsoidal reflector cast from a mixture of fine tungsten powder and an epoxy resin. (4) Hyperboloid reflector similarly cast. (5) Receiving microphone incorporating 15-MHz lithium sulfate $\frac{3}{16}$ in. diam element (Automation Industries unit.

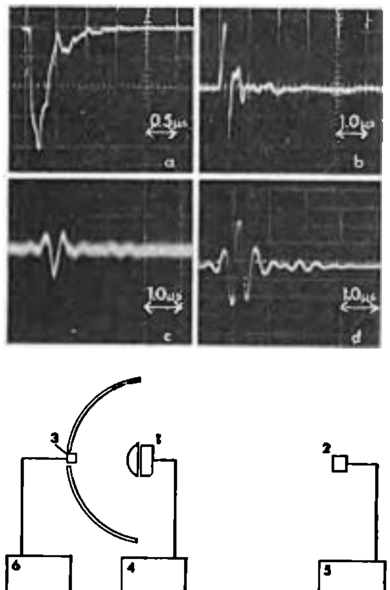

FIG. 4. Waveforms of electrical events at the various elements of the transducer assembly and field probe for various modes of operation of the system shown in line and block form in the lower part of the figure. Time interval reference for: a 0.5 μsec; for b, c, and d—1.0 μsec. (a)—Voltage waveform generated by the electronic pulser (4) across the ultrasonic transmitter unit (1). (b)—Voltage waveform across probe microphone (2) [similar to (3)] placed at the focus of the examining transducer assembly and amplified for cathode-ray tube display by a flat frequency-response amplifier (5). (c—Voltage waveform generated at output of a flat frequency-response amplifier (6) receiving signal from microphone (3), when the acoustic source, driven with the voltage pulse shown in (a) is a probe microphone (2), placed at the focus of the transducer assembly. (d)—Voltage waveform generated at output of a moderately narrowband tuned amplifier (6) (Sperry Reflectoscope UM721—Pulser Receiver 5NFR), when the system is otherwise operated as for (c). This style of amplifier was used for the visual displays illustrated in this paper.

I. METHODOLOGY

The major components of the ultrasonic tissue-visualization facility are shown in the sketch of Fig. 1. The mechanical scanning equipment (1), with sound-coupling tank and supporting structure for the subject appears in the middle of the Figure. The positioning machine for supporting and moving the transducer assemblies is a modified, commercial, automatic turret drill, but since it provides only three rectilinear motions, it has been outfitted with a structure that supports and rotates the transducer unit in the coupling tank. A stereotaxic apparatus for aligning and rigidly holding the head of the experimental animal slides on a track assembly fastened to the sound tank. The direction of movement is perpendicular to the adjacent surface of the tank to facilitate abutment of the head of the animal against a flexible ring-shaped diaphragm in the tank's side. The unit for automatic control of sequences of movement of the positioning system is designated by (2), and an A-type presentation monitor for direct visual examination of echo patterns for single positions of the axis of pulse propagation is designated by (3). The electronic control console (4) includes the oscilloscope display, which is arranged for either direct viewing or photographic recording. Power drivers (5) to the left of the console, provide for pulse electrical excitation of a variety of examining transducer units. An on line digital computer (6) is an integral part of the system; its typewriter input and output (7), in operation, is placed at the console so that a single operator can control the entire system.

A. Materials and Equipment

1. Preparation of Animal

Rhesus monkeys—*Macaca mulatta*—are the subjects in the intracranial visualization studies illustrated here. Since it is desirable to separate the problems associated with transmission of ultrasonic pulses through the skull from those of determining what specific intracranial structural features can be ultrasonically detected, localized, and identified, the animals undergo a craniectomy procedure some time prior to the first scheduled acoustic examination, in order to provide a bone free "window," which exposes the dorsal and lateral aspects of the brain. The craniectomy is performed at a time sufficiently prior to ultrasonic examination so that the scalp is completely healed. It appears that such animals are sufficiently solicitous of their heads in the caged environment, so that damage is not likely to occur to the brain with no protective replacements for the skull over periods of months to a year. For examination, the animal is anesthetized initially by an intraperitoneal injection of sodium pentobarbital (26.5 mg/kg body weight). It is then maintained in a state of light anesthesia over periods of as long as 10 h by the administration of small doses as indicated by the sensitivity of the animal to noxious stimulation.

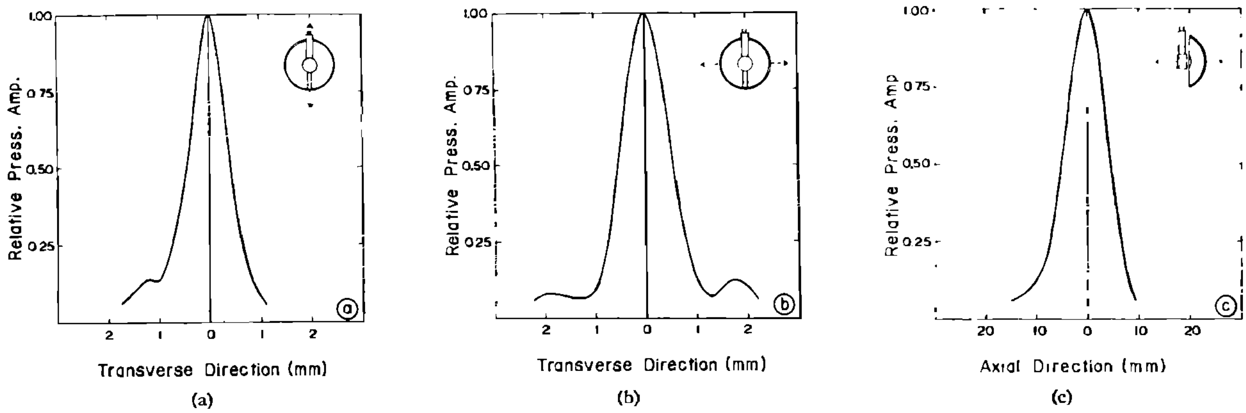

FIG. 5. Relative pressure amplitude at the microphone of the transducer assembly of Fig. 3 in the neighborhood of the focal region for pulses reflected from a metal sphere. (a)—Direction transverse to the beam axis and parallel to the longitudinal axis of the bar that supports the transmitting transducer (see inset, upper right—arrows indicate direction) and at the axial position of the center of the focus. (b)—Direction transverse to the beam axis and perpendicular to the axis of the bar (see inset), which supports the transmitting transducer. (c)—Direction along the beam axis. Symbol zero designates center of focal region in each case.

2. *Support for Animal and Acoustic Coupling Arrangement*

The subject's head is supported in a modified form of Clarke's apparatus[28] illustrated in Fig. 2, which also shows in diagrammatic form the relative configuration of the sound tank in which the transducer assembly is positioned. The head is engaged by the usual arrangement of earbars and infraorbital and mouth clamps, which rigidly maintain the skull of the animal in a fixed position. An unusual feature of this head-fixation apparatus is the provision for rotating the head of the animal about an axis through the ear canals, thus providing one angular degree of freedom of the head axes relative to the axis of the examining transducer (present range of rotation 30°). A reference for locating the focal center of the examining beam with respect to the head-fixation instrument is established by first providing the transducer with a demountable pointer, whose tip coincides with the focal center, and second, by bringing the tip into coincidence with a landmark on the apparatus (such as the center of the earbar axis). Although methods that employ external anatomic landmarks for locating intracranial structure are not characterized by the high degree of accuracy achieved when internal landmarks are employed,[29] such is not needed for the initial positioning of the examining beam with respect to brain features, since, of course, the results of the examination permit one to position it more accurately.

The head-fixation instrument shown in Fig. 2 is placed adjacent to a flexible annular diaphragm, which is fastened to the side of the sound tank. In use, the diaphragm is deflected toward the tank's interior by the animal's head, the top of which protrudes directly into the transmission medium. In use, the marginal surface of the diaphragm surrounding the opening is covered with a caulking compound that insures a liquid-tight seal with the scalp. The transmission medium employed in the tank is either distilled water or a solution of salts, degassed in either case. It is necessary to maintain the medium in the sound tank at a relatively constant temperature, because, of course, the value of the velocity of sound changes as a function of this parameter. A constant value of the velocity is required to insure that the echoes obtained from a common site in the tissue but with different orientations of the transducer system superimpose appropriately for data processing and display. For example, with the path lengths employed here, to limit the variation in position of echoes on an echogram from a single locus to no more than 0.5 mm, requires that the speed of sound in the water vary no more than 0.1%, which corresponds to a maximum variation in the temperature of the transmission medium of 1°C.

3. *Transducer and Acoustic Field Characteristics*

The transducer configuration illustrated in Fig. 3, which has been employed thus far in the visualization facility, is similar to that developed and reported by Olofsson[30] and Hertz *et al.*[31] The outgoing pulses are produced by a 1-in. diam circular PZT plate with a fundamental resonance frequency in thickness mode of 3.00 MHz. The radiation produced by this transducer is collimated to some extent by an epoxy lens fastened directly to the face of the ceramic plate. On the opposite face, the ceramic is backed with a tungsten–araldite matching and absorbing termination to decrease ringing

[28] R. H. Clarke, "Investigation of the Central Nervous System: Methods and Instrumentation," Part I, Johns Hopkins Hospital Rep., Suppl., **19** (Johns Hopkins Press, Baltimore, Md., 1920).

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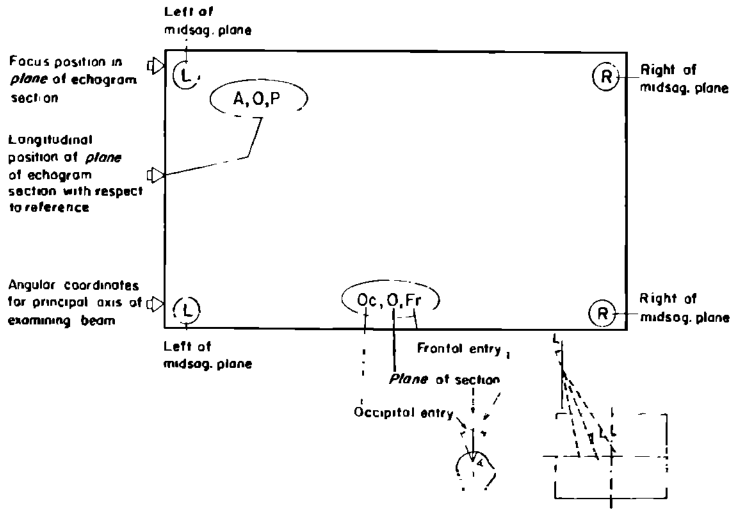

FIG. 6. Echogram coordinate notation.—Any convenient position and plane defined by the head holder can be used—for example midpoint of earbar axis and plane defined by this point and surfaces of the infra orbital clamps for one specific position of the clamping arrangement.

and thus permit the generation of short acoustic pulses under single-pulse electrical excitation.

Sound pulses reflected from Region (2), shown in Fig. 3, which corresponds to one of the focal points of the ellipsoid of revolution (3), are intercepted by (3) and reflected to the hyperboloid of revolution (4), which has one of its focal points coincident with the second focal point of (3). The surface of (4) reflects the sound to its second focal point, which is coincident with the receiving surface of pickup microphone (5). The reflectors (3) and (4) are cast as a composite material, [30] six parts by weight of a mixture of two fine tungsten powders (No. 425 composed of particles 4-5 μ in diameter; No. 427 composed of particles 1-2 μ in diameter), one part by weight of a resin (CIBA Products Company, Araldite No. 502) with the addition of a polymer (Thiokol Chemical Corporation, LP-3) and a hardener (CIBA Products Company, Araldite No. 951). This material is designed to have excellent absorbing properties for ultrasound as well as a high value for the reflection coefficient for such energy incident from a water medium.[32] The distance from the face of (1) to the center of the focal region (2) (Fig. 3), is 12.7 cm, and the aperture angle of the 14.0-cm diam collecting dish as seen from (2) is 0.49 sr. The good azimuthal resolving power of this system is one of its advantages, and for the specific piezoelectric units already described and the electrical driving pulses to be considered next, this value is approximately 0.5 mm in the focal region.

Referring now to Fig. 4, when the driving pulse at the transducer delivered by the electronic pulse generator (4) is of the form illustrated in Fig. 4(a), the acoustic pulse produced is of the form seen in Fig. 4(b), which shows a well-damped acoustic waveform with a "period" of 0.25 μsec as received by a microphone (2) located in the focal region of the transducer assembly—the fundamental resonant frequency of the microphone is 15 MHz and the amplifier (5) has a flat frequency response over the necessary band to preserve the form of the microphone's response. The amplitude of the second cycle (second upward deflection in the Figure) is equal to 0.3 that of the first, and the amplitude of the third cycle is down by a factor of approximately 30 as compared with that of the first. To further elucidate the characteristics of the electroacoustic components the microphone (2) was excited by a voltage pulse with a waveform similar to that shown in Fig. 4(a) and the output voltage from the microphone at (3) was recorded after amplification by two different receivers placed at (6). Figure 4(c) shows the characteristic waveform when a flat frequency-response amplifier is used at (6). However, if a tuned amplifier[33] with a bandwidth of 1.20 MHz centered at 2.25 MHz (3-dB width) is used, the waveform is that shown in Fig. 4(d). Although the quality of the waveform shown in Fig. 4(b) is not maintained by the amplifier system presently used in the display instrumentation, the form is similar to that shown in Fig. 4(d).

Of course, factors other than the pulse duration are important in the determination of range resolution,[34,35] which is approximately 0.5 mm for comparable echo-signal amplitudes, as will be apparent from the echograms. In the commonly used systems, an important factor influencing range resolution is the type of amplification employed—for example, linear or logarithmic. However, in the system described here, the amplifier limitations in the usual form do not apply, since it is

[32] H. P. Schwan and J. M. Reid, "Heart Wall Motion Studies with Ultrasound," U.S. PHS Grant H-3882 (C2) Progr. Rep. No. 1, March (1961), Univ. Penn. Electromed. Div. (Acknowledgment is made to the helpful suggestions of J. M. Reid in regard to construction of the reflector.)

[33] Sperry Reflectoscope UM721 with pulser receiver 5NRF.

[34] J. M. Reid, "Ultrasonic Diagnostic Methods in Cardiology," Dissertation in Electrical Engineering., Univ. of Pennsylvania (1965).

[35] G. Kossoff, D. E. Robinson, C. N. Liu, and W. J. Garrett, "Design Criteria for Ultrasonic Visualization Systems," Ultrasonics 2, 29-38 (1964).

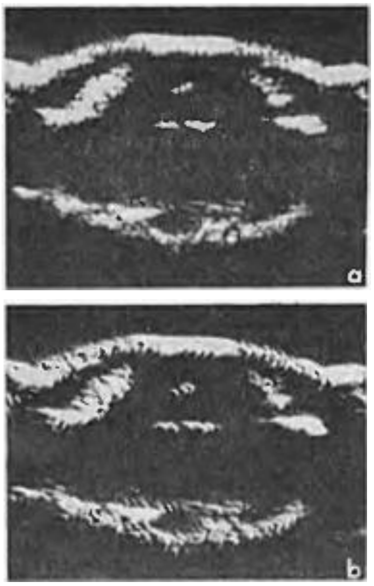

FIG. 7. Echograms of a single transverse section of the rhesus monkey brain. Simple sector scans. (a)—Flat format. (b)—Relief format.

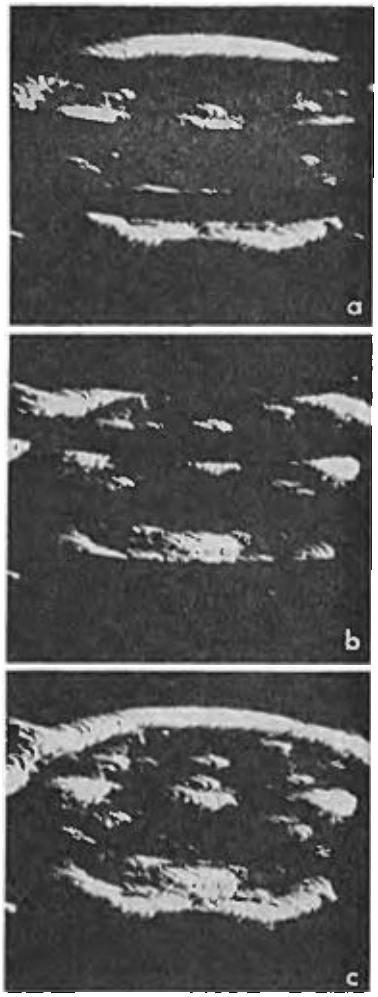

FIG. 8. Construction of an echogram from the echo information contained in individual display bands corresponding to increments of depth within a tissue cross section. (a)—Four display bands of echo data. These bands are separated by three blank spaces that correspond to the echo data presented in (b). The latter also includes a band of echo data to be added to the bottom of (a). (c)—The bands of echo data of (a) and (b) presented as a composite picture.

possible to employ a variety of different dynamic ranges corresponding to different areas of an echogram.

The relative pressure amplitude at the receiver microphone (3), when outgoing pulses are reflected from a 1.6-mm-diam stainless steel sphere is shown graphically in Fig. 5 for various positions of the ball in the region of the focal center and its neighborhood.

4. Scanning and Echogram Axes and Coordinates

The ranges of movement of the transducer provided by the positioning machine in the three mutually perpendicular directions are 100, 50, and 25 cm, corresponding to the lateral, dorsoventral, and anteroposterior axes of the brain for the configuration of head-fixation equipment employed. The rectilinear coordinate positions are determined to 0.1 mm for stationary settings.

For the echograms illustrated in this paper, the axis of rotation of the transducer system was made parallel to the midsagittal plane of the brain. Thus, sector scans of transverse sections of the brain were produced. These echograms, which are photographic records (Polaroid) of the oscilloscope display, are recorded as one-to-one ultrasonic cross-sectional views of intracranial structure. A convention is needed to specify the relative configuration of the transducer position and axes with respect to those of the head during the examination. The position of the plane of section along the longitudinal axis of the brain is designated by the symbol "A" indicating positions anterior to the earbar axis and "P" posterior, in accord with the usual atlas notation. All rectilinear coordinate values are specified in millimeters. A second coordinate indicates the angular orientation of the plane of the echogram, i.e., the plane of section, with respect to the horizontal plane (the latter is determined by *Reid's lines*[36]), each defined by the "center" of an external auditory meatus —determined by the axis of the corresponding earbar—and the lowermost border of the ipsilateral infraorbital ridge—determined by the position of the corresponding infraorbital clamp (see, for example, Ref. 37). A second angular coordinate is required to specify the direction of the principal axis of the examining beam with respect to the dorso-ventral axis (perpendicular to the horizontal plane just defined) of the head. In addition, a coordinate value is required to specify the position of the center of the focal region with respect to the midsagittal plane. All of this information can be shown on an echogram according to the format illustrated in Fig. 6.

[36] Although these lines may not be accurately coplanar before clamping, they are after clamping is accomplished.

[37] S. Bauserman, R. Meyers, and W. J. Fry, "Spatial Variations Between Certain Cranial and Cerebral Structures and the Anterior and Posterior Commissures of the Living Human," Anat. Record 146, 1–6 (1963).

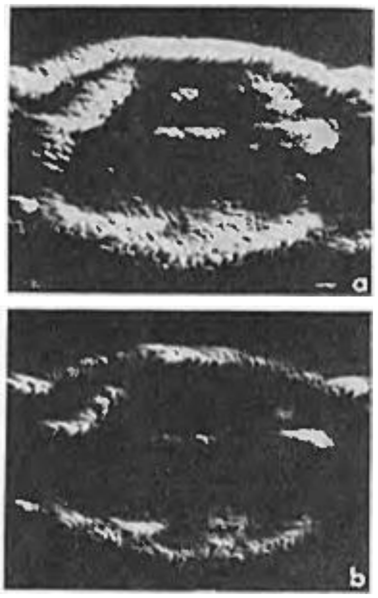

FIG. 9. Echograms constructed from bands for a single transverse section through intracranial structure and displaying structural details for different amplifier-gain settings. (a) Relatively high amplifier-gain settings to exhibit low-level echoes. Echoes from scalp and bone surfaces appear intense with large deflections and little resolution. (b) Gain settings adjusted to exhibit detail in strong echoes from scalp and bone. Note that some echoes internal to the brain that are present in (a) do not appear at all in this echogram.

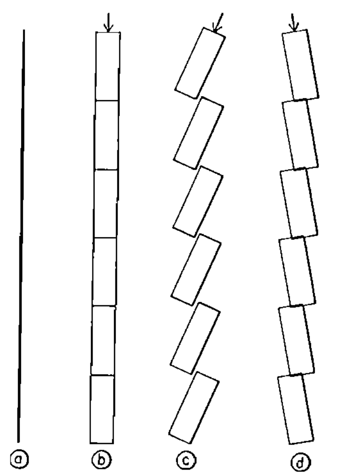

FIG. 10. Diagram illustrating band composition of echograms employed for omnidirectional scanning. Diagrams (b), (c), and (d) correspond to a single-tissue slab and are to be superimposed. (a) Projection of a plane parallel to the echograms on the plane of the illustration, i.e., the echogram planes intersect that of the illustration at 90°. (b)—Cross section of tissue slab examined as in ordinary compound scanning the axis (indicated by the arrow at the top) of the examining pulse train is in the "plane" of the slab. The rectangles correspond to different vertical positions of the focus and a single value of the gating interval for the display. (c) and (d)—Cross sections of tissue examined when scanning with the examining beam axis outside of the plane of the slab is employed. Arrows indicate direction of principal axis of examining beam in each case. Rectangles correspond to the different positions of the focus employed for the band composition in each case. The echo information contained in any chosen number of such compositions can be combined together to yield an omnidirectional scan of the tissue slab.

B. Basic Echogram Development and Related Topics

1. Display Relief

The information received in the form of echoes from tissue interfaces within the structure under examination is presented on the face of a cathode-ray tube as is characteristic of the *B* scan type of presentation, but the format is somewhat different. In the usual method, which is designated here by the terminology *flat* presentation, the intensity of a "spot" on the screen is determined by two factors: (1) the amplitudes of individual echoes; and (2) the number of echoes received from the same structure when viewed from different angles. The new format introduced here, *relief* presentation, provides an additional method of indicating the relative strength of returning signals through the use of spot deflection in addition to intensity. That is, the amplitude of a returning echo, corresponding to a specific position on the screen, can be indicated by a deflection (horizontal for the echograms presented here) of the spot with the magnitude of this deflection proportional to some function of the amplitude of the returning signal. All deflections on the screen can be arranged, for example, to lie in the same direction so that the screen itself presents the appearance of mountain peaks and ranges illuminated from the side. Figure 7 contrasts for a single transverse section through the rhesus brain the usual flat format indicated in Fig. 7(a) with the corresponding relief format in Fig. 7(b). In the relief-style presentation, it is possible to distinguish between different types of compositions of echoes at individual positions on an echogram. For example, display parameters can be adjusted so that a large echo signal produces a large deflection of intermediate intensity while a large number of small signals (corresponding to echoes received from different viewing angles) results in a small deflection of high intensity. It is thus apparent that the relief format provides the possibility of presenting more structural information in a two-dimensional format than does the flat presentation. In general, one might wish to employ a variety of combinations of relief display parameters, including the flat display for greatest accuracy in position measurements. From the experience that has been obtained it seems apparent that the relief format also aids the viewer to more readily distinguished patterns than does the flat presentation.

2. Time-Gated Display

The display console contains the circuitry to permit gating of the presentation on the screen to correspond to echoes from any chosen increment of range. This results in advantages aside from its use in implementing omnidirectional scanning. The transducer assembly has a relatively short depth of focus, and, therefore, in order to achieve optimum resolution capability through out a tissue section, it is necessary that the center of the focus be placed at a series of depths. The gating circuitry provides that only those echoes corresponding to the focal region be presented on the screen. This type of composition is illustrated in Fig. 8, which shows two groups of picture bands in Fig. 8(a) and Fig. 8(b) (four bands in each group), with the widths of the individual bands chosen to minimize spreading of the strong echoes in the presentation while displaying the weaker ones.[38] The composition shown in Fig. 8(c) is accomplished automatically under program control.

[38] Since the work reported here was done, the programming has been completed for adjusting the amplifier gain not only from band to band but also as a function of the position within a band.

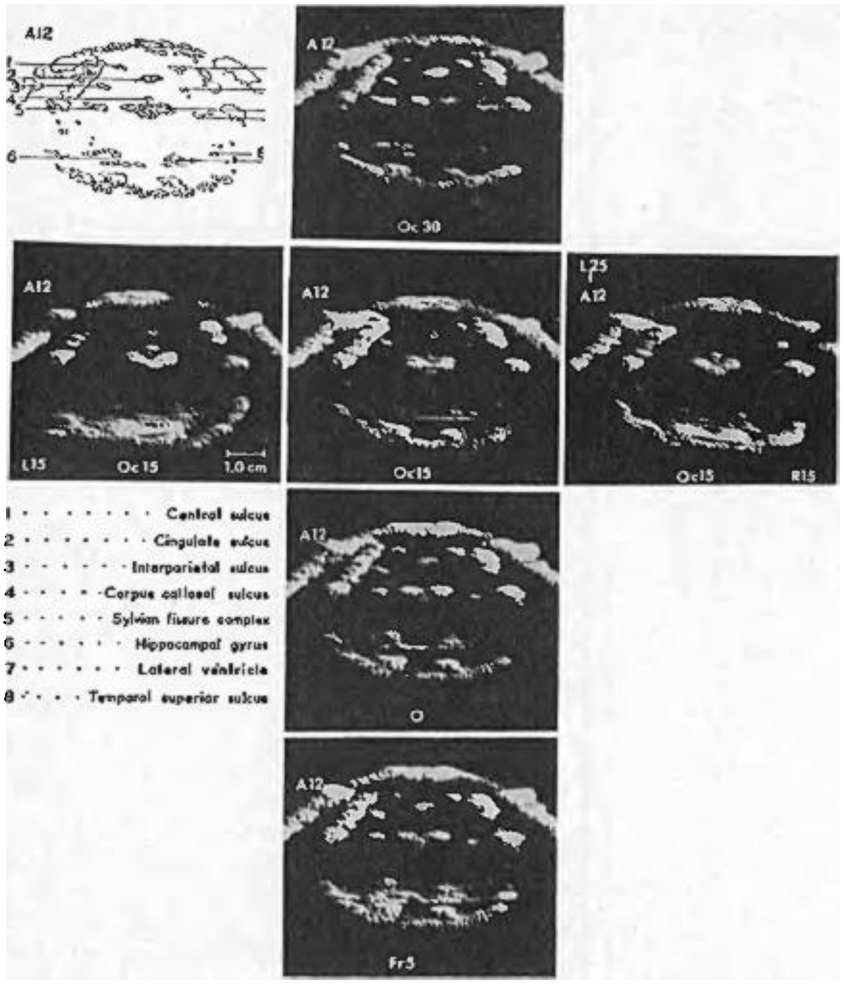

FIG. 11. Composite echogram (upper left) constructed manually from information from the six accompanying echogram photographs. Vertical column of echograms obtained for different positions of rotation of the animal's head about the earbar axis. Horizontal row of echograms is for different orientations of the examining beam axis with respect to the midsagittal plane (axis remains in the same transverse plane). Chart identifies anatomic features manifested in the composite echogram.

It is also apparent that the flexibility provided by the gated display in conjunction with program control of the amplifier gain provides a second advantage in reducing the compromises ordinarily made on the choice of operating characteristics for the receiver amplifier. That is, it is not necessary to (1) balance the advantages of high resolution achievable with a linear amplifier against the wide dynamic range of a logarithmic characteristic; (2) choose a specific form for a time-variable gain characteristic to correct for absorption loss and beam spreading as a function of range. In all systems heretofore employed, compromises between these various characteristics have presented considerable difficulties, and no satisfactory solution has been achieved. However, with the present system incorporating computer control, it is possible to achieve both wide dynamic range and high resolution over most of the area of an echogram and to completely eliminate problems associated with time-variable gain. This follows because the gain of the amplifier can be adjusted automatically for the best presentation of signals.[38]

For increments of no more than a few millimeters, it is unnecessary to adjust the gain on a time-variable basis, because of spreading, for echoes within the corresponding display band, since this factor produces a negligible change in echo amplitude at the microphone for such small changes in range. Similarly, the absorption loss in a few millimeters of tissue does not greatly affect the amplitude of the returning echoes for frequencies of the order of 1 MHz (the average pressure-amplitude absorption coefficient in brain at 1 MHz is 0.1 cm^{-1} at normal body temperature). In any case, the increment of range for which echoes are displayed in a single presentation band can be chosen so that absorption differences do not require time-variable gain; the width of the display, i.e., the range increment, presented for each position of the focus of the system can be decreased as the frequency is increased corresponding to the increase in the value of the absorption coefficient with the frequency.

With respect to dynamic range and resolution, it is possible to achieve much better combinations with the present system than with less sophisticated instrumentation. For example, it is possible to employ an amplifier that is essentially linear over most of the amplification range and to change the gain as a function of the amplitude of the echo signals received from each specific site. This can be accomplished entirely automatically by the on-line computer. To implement these features, the axis of the rotary sector scan has been provided with an encoder sensor for the precise determination of the angular position of the axis of the transducer assembly.[39] As a specific example, the reflections that appear in Fig. 7, arising from the bone and from the external surface of the scalp, which are of large amplitude compared to those arising from some of the other interfaces, could be presented with low amplifier gain to exhibit high resolution (that is, resolution of detail in the signal shape), and low-amplitude signals could be presented with high gain and equal resolution. The desired result can be approximated by producing echograms with the gains for individual bands adjusted to different levels and with the band positions chosen to display to the best advantage the observed signals. This is illustrated in Fig. 9, where echograms corresponding to a single cross section are shown for two sets of values of the gain for the different bands, one set to exhibit the details in high-intensity echoes and the other to exhibit the detail in and also the existence of lower-level echoes from within the brain.

C. Composite Echogram Development

1. Contributions to a Composite Echogram

Tissue interfaces are identified, of course, by detecting partially reflected incident ultrasonic energy coming from within *cross sections* of the structure under examination. These cross sections are in the form of slabs with a thickness determined by the *beam width* of the transducer system and by certain characteristics of the associated electronic processing system. When the principal axis of the examining beam remains in the slab corresponding to the echogram, then the echo information obtained is that characteristic of the usual compound scanning methods. Obviously, a series of echograms can be recorded with the examining transducer in different fixed rectilinear positions (principal axis remaining in the slab), with the axis of the examining beam undergoing an angular sweeping motion to achieve sector scanning. A group of such sector scans can then be combined in order to achieve a composite, a procedure that is done automatically by instruments employing compound scanning. However, it has been instructive during the studies with the system described herein to examine in detail series of echograms corresponding to individual sector scans and to combine the information by manual methods. The resulting experience provides the rules for designing programs for automatic composition.

By rotating the head of the animal about the earbar axis, by means of the adjustment on the head holder, it would be possible to obtain any number of sets of individually mutually parallel planar echograms of the type just described, i.e., with the principal axis of the examining beam always within the slabs corresponding to the echograms. The composition of the echo information from a number of such nonparallel sets of echograms into a single set would constitute a very extensive task requiring complex three-dimensional reconstruction. Manual composition would be extremely impractical, and its advantages at the present stage of the work in providing criteria for developing programmed computer composition would then not be forthcoming.

[39] This feature was not available at the time the results on intracranial structure, which are included in this paper as an illustration, were obtained.

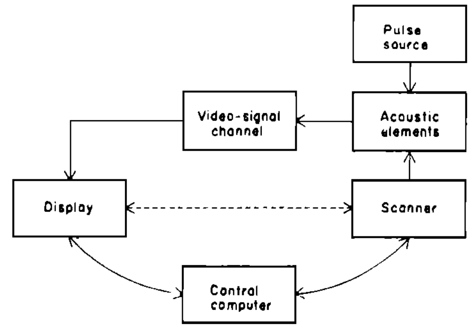

FIG. 12. Electrical and mechanical linkage pathways between the various elements of the visualization system.

However, by using the omnidirectional scanning method, it is possible under computer control to obtain much additional echo information to incorporate readily into a *single* set of parallel echograms compared to the amount of information obtained by scanning with the principal axis always within the corresponding tissue slabs. The omnidirectional scanning is implemented by obtaining echo data with the head of the animal in various rotated positions about the earbar axis. The arrangement of the bands is illustrated in Fig. 10 for three angles of orientation (one in the plane of the slab) of the examining beam axis with respect to the plane of the slab.

2. Manual Composition of Echograms

It is apparent that the construction of an echogram, employing echo data obtained by omnidirectional scanning, composition by bands, relief presentation, and, in the next phase of the work, program control of amplifier gain within a single band, constitutes a complex process. At the present stage of the studies of brain, it is apparent that manual composition of the information from various individual echograms is a necessary stage in the development of criteria and procedures for ultimately combining all the information in a completely automatic fashion. At the present time, composite echograms are constructed by transferring the information obtained onto a transparent overlay on which all the pertinent echo information can be marked. This method of manual composition, illustrated in Fig. 11, provides some very definite advantages at the present stage of development of the echo data-processing methods, even though it is time consuming.[40] For example, it provides the equivalent of viewing the tissue at those gain settings for the receiver amplifier most appropriate for the various structural features. Another advantage is the elimination of inaccuracy in the registration of overlapping patterns. It is possible with the overlay method to superimpose accurately echo information common to two echograms in the immediate neighborhood of pattern information that is not common, thus permitting the transfer of the noncommon information to the composite without the blurring of the detail caused by lack of perfect registration. In this regard, it should be noted that registration is not only a function of the accuracy of geometric positioning of the transducer assembly and the precision in electronic tracking, but it is also influenced by (1) the small differences in the transit time of the sound along composite propagation paths through coupling medium and tissues as the same structural features are viewed from a variety of orientations, and by (2) the refraction introduced when the sound enters the tissue at large angles of incidence. That is, in general, returning echo information must be examined to determine from the pattern itself how superposition should be accomplished in constructing composites. This can be done automatically only with rather sophisticated data processing. The use of a manual method, for example, employing overlays of the type described, aids in the development of criteria for incorporation into a machine method.

II. INSTRUMENTATION ORGANIZATION

A. System Structure

Since the acoustic soft-tissue visualization system described in this paper is intended to be a highly versatile investigative tool, it is organized differently and is considerably more elaborate than ultrasonic instruments that have been designed in the past for diagnostic use. Parts of the system can be modified or replaced as new techniques are developed, with the other parts either being unaffected or readily adaptable to the changes. Fundamental to this versatility is the basic structure of the system as shown in Fig. 12 at the stage in which it was when the visualization results included here were obtained. A digital computer is used to control and coordinate the operation of various subsystems; i.e., a distinguishing characteristic of the individual system components is the ability to be controlled and observed by a computer. Though all the inter-

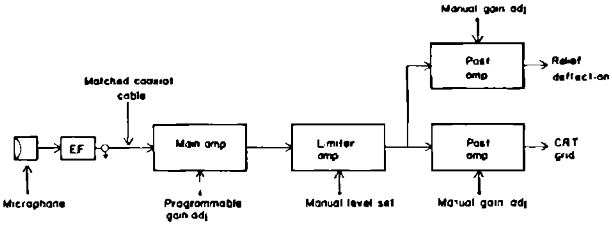

FIG. 13. Video-signal-channel component of Fig. 12.

connections are not shown in Fig. 12, every portion of the system is dealt with in some way by the computer. The advantages of such an arrangement have been found to be so marked that future additions will be designed to allow an even greater degree of computer control.

In the present system, the numerically controlled positioning machine, or scanner, which supports the acoustic transducer assembly, has been modified to operate directly from computer commands. The echo patterns presented on the display console are also under direct computer control and while some direct communication has existed between the scanner and display, the major link between the two for obtaining the results reported herein was via the computer and its stored programs. Elimination of the direct link has since been accomplished so that complete program control is now available for the display unit.

In general organization, the present detection amplifier or video-signal channel follows conventional design, though some of its detailed properties are of interest here. As shown in Fig. 13, echo signals received by the microphone are transmitted by an emitter-follower preamplifier (built as an integral part of the microphone assembly) through a matched coaxial cable to the main amplifier. Most of the parameters that determine the nature of the signal eventually presented to the display are contained within the main amplifier; gain, frequency and transient responses, amplitude characteristics, and noise are the more important ones. A separate stage contributes the limiting or overload characteristic, though on occasion a logarithmic main amplifier has been used, and then the limiting stage is omitted. Following the limiting amplifier are two post-amplifier stages to deliver the video signal to the display cathode-ray tube grid and to the deflection circuits for the "relief" deflection. As can be seen in Fig. 13, nearly every stage in the signal channel has some provision for adjustment, either manually or through program control. For example, the degree of relief effect can be varied over a wide range by adjusting the controls on the post amplifiers, and the nature of hills can be changed from the peak type to plateaus by adjusting the limiter stage. As experience is accumulated, at least some of these controls will be placed under program control.

[40] The construction of composite echograms in the manner of the usual B-scan presentation is not appropriate for achieving the resolution capability and the visualization of anatomic detail that can now be attained with manual composition. Much additional sophistication is necessary in the computer handling of echo data in order to achieve the capability of the latter, as is apparent from the ensuing discussion of this Section.

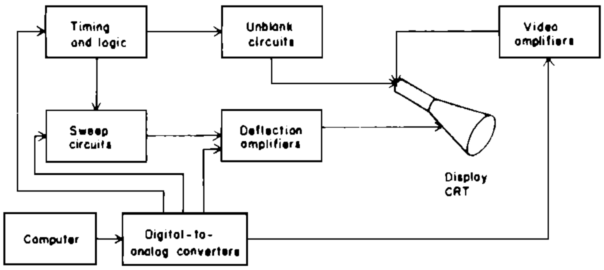

FIG. 14. Display component of Fig. 12.

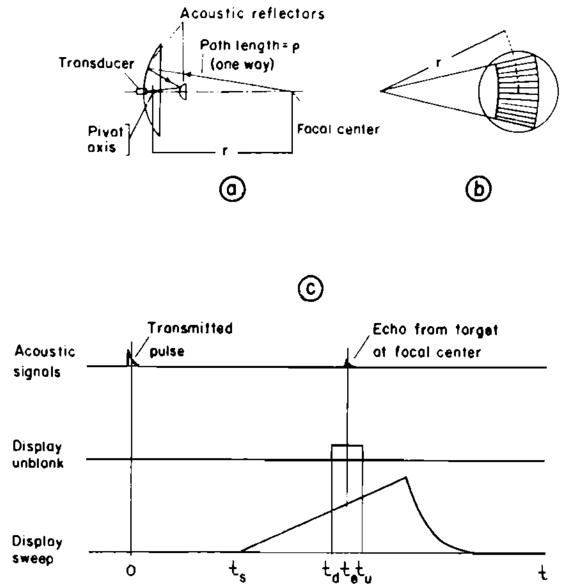

FIG. 15. Acoustical and mechanical characteristics of the transducer assembly and electrical events in the display section of the examining system. (a)—Typical acoustical pathway and a specific mechanical pivot axis position. (b)—Diagrammatic representation of cathode-ray tube face showing angular sector display for a single position of the pivot axis of the transducer assembly. (c)—Time sequence of events associated with the displaying of a signal on the screen of the presentation unit.

B. Computer–Display Link

To give the computer program complete control over the echogram presentation, the display circuitry must be organized in appropriate fashion. Parts of the system are conventional, as shown in Fig. 14, such as the deflection amplifier and unblank circuits, while others are special and programmable, such as the sweep and timing circuits. Program control is accomplished by converting digital information from the computer into separate control voltages for each circuit by means of a multichannel digital-to-analog converter. For the echograms presented in this paper, such program control was provided for the horizontal and vertical positions of the pattern, the center and duration of the range interval to be displayed, the time delay between transmitted examining pulse and initiation of the display sweep, and the video amplifier gain.

The use of these programmed parameters with the acoustic arrangement of Fig. 3 [shown in diagramatic form with coordinate notation in Fig. 15(a)] demonstrates how the system can adapt to a wide variety of acoustic situations. Suppose that the assembly scans by rotating about the pivot axis indicated and that it has a focal center at a distance r from this axis. The display pattern for such a scanning motion is indicated in Fig. 15(b), with a target at the focal center shown near the middle of the display. To produce this display, the programmed timing circuits are adjusted by the computer to produce the waveforms shown in Fig. 15(c), according to the following program computations in which the symbols have the following meanings: d is the depth of focus of the array; $2P$, the total sound-path length; r, the radius from mounting axis to focal center; t_d, the time delay to initiation of range unblank; t_e, the time from emission of pulse to receipt of echo from focal center; t_r, the time from initiation of sweep to display of echo signal; t_s, the sweep delay; t_u, the time to end of range unblank; and v, the sound velocity.

First, it is observed that $t_e = 2p/v$. However, for the display sweep to appear to radiate from the pivot axis, the echo must occur at a time t_r after the start of the sweep, such that

$$t_r = t_e - t_s = 2r/v. \tag{1}$$

Therefore, the sweep delay t_s is set by the program to satisfy

$$t_s = t_e - 2r/v = 2(p-r)/v. \tag{2}$$

For an operating depth of focus of the assembly equal to d, the display is activated for a range time interval, $t_u - t_d$, as follows:

$$t_u - t_d = 2d/v. \tag{3}$$

Finally, the range time interval is set to start after a delay t_d as follows, where it is assumed the focus is to be centered in the interval

$$t_d = t_e - d/v = (2p-d)/v. \tag{4}$$

Thus, it can be seen that once the display timing circuits have been made programmable to the extent indicated here, they are adaptable to acoustic configurations with wide ranges of combinations of focal lengths, sound-path lengths, and depths of focus. If the sweep speed were also programmable, coupling media characterized by different values of the sound velocity could also be accommodated; consequently, such a provision is planned for the future.

C. System Programming

Of major importance to achieving the capabilities of the instrumentation system is the computer programming for on-line application, including the communication arrangements for human-operator participation. It is essential, of course, that all intercommunication

TABLE I. Reproduction of typical-system-operation dialog.

COMPUTER OPERATED SCANNER PROGRAM	initial computer comments and requests
GIVE X	operator entry for X coordinate
X520	
GIVE Y	operator entry for Y coordinate
Y200	
GIVE Z	operator entry for Z coordinate
Z105	
GIVE F	feed rate F for motions
F500	last initial operator entry
X521	new X coordinate request (by op)
R8.1	request to move *R*ight 8.1 mm
X AXIS UPPER LIMIT, 525.00, EXCEEDED	computer warning
S	request *S*ummary of boundaries
X BOUNDARIES ARE 515.00 and 525.00	
Y BOUNDARIES ARE 195.00 and 205.00	computer response
Z BOUNDARIES ARE 100.00 and 110.00	
F BOUNDARIES ARE 10.00 and 5000.00	
B	initiate *B*oundary change
GIVE BOUNDARY CONDITIONS FOR NORMAL MODE	computer response
R530	new Right boundary entry
X54W..ERR..	typographical error and computer notification of the fact—
R8.1	request to move Right 8.1 mm
T	request *T*yping of present position
X 529.10	
Y 200.00	computer response
Z 105.00	
F 500.00	
A	request to change *A*nimal mode
ANIMAL MODE	computer response and request for data
GIVE EARBAR ZERO LOCATIONS	
X COORD	X coordinate of earbar zero
X523	
Y COORD	Y coordinate for earbar zero
Y201	
Z COORD	Z coordinate for earbar zero
Z107	
A2.1	request for position: *A*nterior 2.1 mm
D3.25	request for position: *D*orsal 3.23 mm
L4.3	request for position: *L*eft 4.3 mm

between operators and the system be organized in terms familiar to the operators, and for rapid exchange of information, be implementable with a minimum number of artificial conventions or codes to remember. To accomplish these objectives, the programs for the present system are written to receive all commands via the computer typewriter, by using simple mnemonic abbreviations for the tasks to be performed. Few special control settings are involved, so that the typewriter page contains nearly all communications with the system and it can be used with little supplementation as a permanent record of the operations performed during visualization procedures. Another requirement for a system with operator participation is the use of many error checks, warnings, and other messages to indicate the state of the system and assist the operator in making decisions. When these are included, the computer typewriter page takes on the appearance of a dialog between the system and the operator and thus becomes a more easily interpreted record of system use.

An example of this dialog (including some of the commands used for manual scanner motions and computer messages) with its interpretation is shown in the reproduction of a typical typewritten page in Table I. Simple requests and messages are exhibited in the top half of the sheet. Below the middle of the page is a request for the program to shift to a second mode of operation, A for Animal, which allows examination-position coordinates to be requested in a more convenient form for animal-examination procedures. In this mode, the mnemonic abbreviations are in the experimenter's language and refer to locations in the animal brain in standard stereotaxic notation. The scanner coordinates of the reference position are determined prior to entry into this mode and are requested by the program immediately upon entry. Thereafter, as shown in the lower half of Table I, the experimenter can request positions such as *A*nterior 2.1 mm, *D*orsal 3.23 mm, etc., corresponding to coordinates in a brain atlas. The program computes each new set of scanner coordinates, taking into account the orientation of the subject's head.

In addition to the simple motions listed in Table I, the program allows the operator to specify the angular orientation from which to view the subject. Since the animal's head can be rotated in the holder, as described in the Section on methodology, the computation of the scanner coordinates involves all three axes according to the following transformations (see Fig. 2 for identification of coordinate symbols with specfic instrument axes):

$$X=X_0+R+r\sin\theta,$$
$$Y=Y_0+r(1-\cos\theta)+D\cos\phi+A\sin\phi, \qquad (5)$$
$$Z=Z_0-D\sin\phi+A\cos\phi.$$

(See Table II for definitions of the symbols used in Eq. 5.)

The expressions for computing the values of the display-position coordinates are somewhat different in form from Eq. 5, and they include an angular coordinate variable for designating rotation of the display pattern on the presentation screen.

Expressions 1–5 illustrate the ease with which the system can be adapted to a variety of situations. Only the analytic expressions, used in the scanner or display subprograms, need be changed to implement a desired scan pattern or display–scan relationship.

A final provision of the operating program makes possible the machine assembly of composite echograms from the data obtained from a number of separate scans. All the values for the scanning and display parameters for the individually scanned segments (overlapping or

TABLE II. Definitions of symbols used in Eq. 5.[a]

X,Y,Z	scanner-position coordinates; X,Y coordinates in plane perpendicular to the horizontal plane of the head holder for $\phi=0$, [X is the distance to right, $R(-)$, or left, $L(+)$, of midsagittal position; Y, the distance above, $D(-)$, or below, $V(+)$, the horizontal plane (when $\phi=0$ the value of Y is equal to the value of D or V)]; Z, the distance anterior, $A(+)$, or posterior, $P(-)$, to the plane of X and Y (when $\phi=0$, the value of Z is equal to the value of A or P)
X_0,Y_0,Z_0	scanner position for placing acoustic focus at earbar zero with viewing angle θ at zero
r	distance from mounting axis of transducer to focal center (see Fig. 15)
θ	viewing angle within plane of section relative to midsagittal plane (positive when beam axis is directed toward the right of this plane in the negative x direction)
ϕ	amount of angular rotation of animal's head about earbar axis (positive when head is rotated for occipital entry—see Fig. 6)
A,P	anterior, posterior position of cranial site to be examined in atlas coordinate system (A, anterior to earbar zero, Z, positive in the anterior direction, P, posterior to earbar zero)
D,V	vertical position of site to be examined in atlas coordinate system (D, dorsal to earbar zero, Y negative in dorsal direction, V, ventral to earbar zero)
R,L	lateral position of site to be examined in atlas coordinate system (R is to right of earbar zero, x is negative, L is to left of earbar zero)

[a] Note that the algebraic signs of the terms on the right of Eq. 5, which contain the cranial coordinate symbols, change with the interchanges of symbols.

nonoverlapping as desired) of an echogram section or a series of such sections can be stored. Parameter values are grouped in blocks, each corresponding to the settings for an individual segment of an echogram,. Each block is assigned an identification number when stored, and it can be recalled by this number. In this way, a large number of combinations of scanner positions, viewing angles, and corresponding sets of display parameters is made available to the operator for easy reference. The blocks of values can also be punched on tape automatically, on command, to become part of a permanent library for future use.

III. CURRENT AND FUTURE PROGRAM EVOLUTION

As is typical of an investigative program, experience in using the visualization system has revealed desirable modifications. The present degree of program control has demonstrated the value of a programmable system structure and has shown that this technique should be extended to include other functions.

A recent modification already mentioned is the addition of a digital angle encoder to the rotary scan mechanism to allow the computer to read the angular orientations of the transducer array. This addition eliminates the direct transmission of information from scanner to display shown in Fig. 12 by the dotted line. The computer can now read the angular position, compute the corresponding display parameters, and so completely control the display. In the future, it will also have program control over other rotary motions and over direction and speed of travel of all degrees of freedom, thus providing complete control of all aspects of the scanning motions, and the relationship between them and the echogram presentation.

Another feature currently being incorporated involves the video-signal channel, and it constitutes the initial step toward automatic processing of echogram data. The limiter amplifier shown as a component in Fig. 13. will be eliminated and a *threshold* detector circuit will be added to observe the magnitudes of the signals from the main amplifier. Since the main amplifier gain is programmable, the computer will be able then to measure signal amplitudes in terms of the gain settings required to bring them to the threshold value. When combined with program-controlled motions and the time-gating facility in the display control circuits, the system will be able then to read and store signal amplitudes reflected from any tissue site for any viewing orientation.

Along with the instrumentation changes comes extensive new programming, partly by necessity for the equipment operation, but mostly because of the greatly expanded system capability. With all the motions under program control, programs can be prepared to supervise longer and more complex scanning sequences, and operator commands will be more closely related to the functions to be performed and less concerned with equipment characteristics.

The ability to measure video-signal amplitudes will make it possible to scan tissue, prior to echogram recording, for the purpose of determining optimum gain settings for each individual portion of the presentation. The computer will then be able to exercise the same type of judgment that now requires human study of a number of photographs followed by tedious adjustments. Finally, when a sufficient repertoire of subprograms of the foregoing types has been developed, complete composite echograms of the kind described in the methodology section can be automated. As experience accumulates, the computer assumes an increasingly comprehensive rôle in decision making and implementing the examining conditions. The oncoming new computer programs will be designed to make ultrasonic visualization increasingly useful to those individuals to whom the ultrasonically detected and displayed features of tissue structure are significant and useful, by improving dialog communication links between the on-line computer and its human operators.

IV. SUMMARY

A versatile and sophisticated ultrasonic tissue visualization system is described. It incorporates an on-line medium-size digital computer that provides wide flexibility with respect to comprehensive scanning (omni-

directional); dual parameter display (relief); dynamic range and resolution (gating and gain of receiver amplifier under program control); incorporation of changes indicated by accumulating experience.

Omnidirectional scanning provides for viewing tissue cross sections not only with the principal axis of the examining beam lying within the cross section, but also for a range of angular orientations of this axis with respect to the section. This means that for a specific cross section in the tissue, the corresponding echogram in general includes echoes from interfaces that would not be manifested with the usual compound scanning methods.

Relief display introduced here into echograms constitutes a useful advance in presentation methodology, since it appears to aid the viewer in identifying significant signal patterns. It also provides a means of distinguishing between different compositions of echoes at single positions, e.g., between that corresponding to a wide-angle scattering center and that for a specularly reflecting interface.

Echograms corresponding to an entire tissue cross section are constructed in stepwise fashion under program control from a group of nonoverlapping (or overlapping, if desired) partial echograms (each the shape of a sector of a ring), each corresponding to an increment of range. The focus of the transducer assembly is centered at a depth corresponding to the middle of the range, and the receiver amplifier gain is adjusted for optimum display characteristics for the range increment displayed. Thus, the function of time-variable gain and the conflicting requirement of wide dynamic range and high resolution in the receiver amplifier in the usual forms of equipment are replaced and resolved, respectively, by computer control of the gain in the present system. This type of control makes it possible to achieve optimum azimuthal resolution over an entire echogram and to present both strong and weak signals lying in different range increments, without losing the detail characteristic of logarithmic amplification. (Program control of the gain as a function of position within the individual ring sectors will remove the remaining limitation.)

The on-line computer implements major modifications in the operating characteristics of the system, which should undergo continuing evolution as other tissue structures are examined. Major changes can be made in processing of echo data, composition of echograms, and scanning sequences, without involving the large expenditures of funds and time that are characteristic of special purpose instrumentation.

The auxiliary apparatus and a procedure for applying the system to the examination of intracranial structure are described, and typical echograms of brain cross sections of the rhesus monkey, under the condition that the sound does not traverse the skull bone, are illustrated.

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