A computerized echoencephalograph

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A new echoencephalograph is described which automates the measurement of midline shifts. A built-in digital computer identifies echo patterns, performs all calculations, and indicates midline shift directly in millimeters, allowing a graphic record to be made of many, rapid, individual echo determinations.

KEY WORDS · echoencephalograph · computer

Echoencephalography has slowly become recognized as a valid tool for detection of brain midline shift, and an extensive body of literature has accumulated. However, the technique has not become a routine clinical procedure. Some clinicians adopted the method, lost confidence, and then abandoned it when confronted with inconsistent findings. The reason for this is that the determination is frequently more difficult than is readily apparent. Being aware of this, most experienced echoencephalographers have advocated that the present procedure be performed only by thoroughly trained medical professionals. This restriction on the method effectively limits its use to centers that already have alternative diagnostic capabilities, and even at those centers it may not be available on a 24-hour basis. In a series of critical investigations of present operational techniques, many workers have developed methods pointing the way toward more advanced devices for overcoming existing drawbacks.

The purpose of this report is to describe an instrument, developed by the authors over a period of several years, which uses computer technology to overcome most of the operational errors associated with the use of conventional oscilloscope-type echoencephalographs. An independent analysis of the laboratory and clinical characteristics of this instrument has been performed by another investigator.

Physical Basis of Measurement

The ultimate limit on the accuracy of the echoencephalographic technique is set by the physical interactions of ultrasound with tissue. These properties have been abundantly described. Specifically pertinent are:

1. Wavelength limitation. For intracranial work at a typical frequency of 1.5 MHz, the minimum theoretical "single-cycle" uncertainty is about ± 1 mm.
2. Physics of ultrasound interactions at tissue interfaces. Contributing to errors are such effects as scatter, refraction, beam dispersion, interference, and tissue velocity differentials.
3. Echo envelope rise time and wave shape. Although the electrical energy injected into the crystal to generate the transmitted acoustic wave is in the form of a short burst, the crystal requires a period of time before it can overcome its mechanical inertia. Thus, a delay occurs in the build-up of the oscillatory motion of the crystal faces. Similarly, there is further degeneration in the acoustic wavefront at the crys-
tal-skin and each successive interface. Which cycle of the wave first exceeds the input threshold level determines the approximate delay by which the "echo peak" is displaced from its initial arrival. Here, the instrumentation can introduce errors of which the operator is totally unaware.

In addition to the variations introduced by the mechanisms of energy interaction, there are anatomical irregularities. Since the reference for midline structure localization is the transverse head size, asymmetry may distort the data. This could arise from congenital and developmental skull anomalies, scalp swelling or bone displacement resulting from trauma or surgery.

The source of brain echoes, the interfaces themselves, constitute poor reflectors at best because of their size, shape, and small acoustic impedance differentials. Angular distortion of midline structures, which can be caused by intracranial mass lesions, even further reduces the effective cross section for back reflection. Of more importance is the fact that the reflecting interfaces of normal midline fluid-filled cavities, such as the third ventricle and the inter-hemispheric fissure, are at the brain-fluid junctions rather than in the anatomical midline. Since the normal width of the common midline landmark, the third ventricle, can vary from 3 to 6 mm data spread of this magnitude will be added to the other determination uncertainties. These combined physical and anatomical considerations result in a theoretical limiting accuracy of the method to approximately ±2 to 4 mm.

For the quantitative location of brain midline structures, it is necessary first to find the true midline of the head by measuring the total head diameter and dividing by 2. This measurement must be made perpendicular to the mid-sagittal plane in line with the particular beam path length along which the midline echoes are generated. This is done most accurately by determining, 1) the one-way transit time of an ultrasound pulse from one crystal, used as a transmitter, to a receiving crystal on the opposite side of the head, or 2) one-half of the out-and-return time for echoes from the skin-air interface on the opposite side. If the latter, or single-crystal technique, is used, the operator must carefully analyze the complex distal echo pattern received from the far side of the head in order to identify correctly the skin-air interface. Although the distal echo pattern appears to be simple, it may actually be rather difficult to interpret. Ideally, there are two major echoes (due presumably to CSF skull and skin-air acoustic impedance mismatches) but there can be three or more. Not infrequently, there are also reverberations (or internal partial reflections) of signal energy trapped between these strongly echoing interfaces. In short, there may be echoes generated either by different interfaces or by the same interfaces at different times.

Simultaneously with the determination of the true head size from transit time of the distal head echoes, the location of the brain midline must be measured. This requires the correct identification of the midstructure echoes from among the large number of brain interface echoes. These are usually displayed on an oscilloscope as electronically smoothed wave forms, which appear to the observer to be essentially identical, regardless of their origin. The only readily observable information is the echo arrival time, from which the location of the reflecting surface is to be inferred. When they can be evoked, there are certain properties of echoes which can help identify midline structures such as their greater amplitude, spacing (e.g., characteristic M-echo doublet pattern), and the possible presence of pulsation.

**Conventional Instrumentation**

In this context, consider the conventional oscilloscope-camera echoencephalograph. With this type of instrument, the operator simultaneously concentrates visual attention on an oscilloscope, manually orients a detector-probe on the patient's head, and then manipulates the instrument controls to obtain an echo pattern upon which a diagnosis is to be based. These devices provide manual variability of complicated modes of electronic amplification, adjustment of high voltage or pulse power, signal cut-off and damping in addition to the usual oscilloscope controls. This combination of information complexity (multitude of echoes) and complete freedom to enhance or, alternatively, to sup-
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press basic data, place an unusual burden of discrimination upon the operator. Considerable skill is required in the manipulation of controls, as well as knowledge of neuroanatomy and experience in echo pattern recognition. Since it is possible to locate visually and then to amplify echoes from any region of the head, it is obvious that the operator will seldom be completely "unsuccessful" in an oscilloscopic echo determination. In effect, the operator can select and record from an infinite number of patterns. If he has prior knowledge of the suspected or confirmed diagnosis, there may tend to be an artificially high correlation of the data. If we consider the dynamic range over which both the echo patterns and the display can be varied, it is difficult to imagine another diagnostic procedure in which experience and objectivity are tested to such a high degree. This subtle aspect of the problem has been studied extensively. Since acquisition of data, interpretation, and diagnosis are frequently simultaneous and interdependent, some degree of observer subjectivity and interpreter bias is unavoidable. Therefore, it would be desirable to isolate, to the greatest extent possible, the data from the interpretation and diagnosis. Furthermore, the demands upon manual and visual attention make it very difficult to concentrate upon the most important aspect of the echoencephalographic measurement: location and orientation of the detector probe.

Automatic Midline Computer

Restricting the application of the technique solely to the location of midline structures, and with all of the foregoing factors in mind, an instrument design was undertaken to achieve the following goals:

1. Substitution of automatic pattern recognition criteria for operator decision
2. Concentration of operator attention on the application of the detector probe to the patient's head
3. Acquisition and recording of enough single-orientation data values to establish statistical confidence in the echo pattern detected.

The evolution of the design involved the elimination of both visual observation and manual instrument control during the determination. Midline structure and farside skull (distal) echoes are analyzed by the pattern recognition program of a built-in digital computer. All echo identification and distance measurements, as well as final direct display of the calculated shift, are accomplished automatically. In place of the oscilloscope display, all information about the progress of the determination is fed back to the operator by audio signals. Thus, the operator is free to focus total attention on probe positioning and orientation. Successive echo locations, indicated directly in millimeters of shift on a digital display divided into intervals of 2 mm, can be plotted by the operator to give a permanent record graph.

The principle of operation of the instrument is illustrated in Fig. 1. The transmit search pulse triggers the timing clock. Echoes are amplified and gated into the Distal and Mid memories. These memories are interrogated by the pattern recognition circuit, which either starts the computer or resets the whole system, depending upon whether or not the echo patterns received were acceptable.

Upon receipt of a correct pattern of distal and midechoes, the computer performs all of the arithmetic operations necessary for the determination of the displacement of the midstructures from the centerline of the head. The distal and midstructure echo groups are analyzed on the basis of 1) number of individual echoes in a group (one, two, or more than four), 2) amplitude, and 3) time of arrival. The transit times to the leading edges of the echo pulse trains are measured by a 1.5 MHz crystal-controlled clock.

The basis of acceptance of the distal echo pattern is the receipt of an echo doublet that exceeds a fixed amplitude discrimination level and arises in an interval gate that is opened approximately 10 cm beyond the transducer. The round-trip time from the detector to the skin-air interface (the leading edge of the second echo of the doublet) is stored digitally as a number of timer counts. This successful measurement triggers a 250 Hz audio tone to alert the operator and simultaneously institutes a search for echoes in the midhead region. Thus, every midline determination is normalized to the exact to-
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ULTRASONIC TRANSUDER
PULSE RATE
500 Hz.

250 Hz. AUDIO SIGNAL, COINCIDENT WITH LOCATION OF DOUBLE DISTAL ECHO

COMPUTER
ANALYZES MIDLINE REGION ECHOES. IF SINGLE LARGE ECHO IS FOUND, ITS POSITION IS READ OUT IN MILLIMETERS TO DIGITAL DISPLAY.

500 Hz. AUDIO SIGNAL, COINCIDENT WITH READ-OUT

MID-GATE

IF NO LARGE ECHO IS FOUND, OR IF TWO OR MORE ARE FOUND SIMULTANEOUSLY IN A SINGLE SCAN, COMPUTER RE-CYCLES AND STARTS SEARCH FOR DISTALS AGAIN.

COMPUTER SEARCHES FOR DOUBLE DISTAL, MEASURES WIDTH OF SKULL, THEN DETERMINES TRUE MIDLINE LOCATION AND OPENS GATE FOR MID-ECHO SEARCH.

Oscillator Amplifier

DISTAL SEARCH

MID-ECHO SEARCH

10 mm 0 10 mm

SKULL INNER TABLE
DOUBLE DISTAL ECHOES
SKIN-AM AIR INTERFACE

Fig. 1. Flow diagram illustrating principle of operation of the midline computer (see text).

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tal head size at the location and orientation of the detector beam at that search time.

The first single echo or the first of two echoes that are separated by no more than 4 mm ("M echo") that has an amplitude above a fixed discrimination threshold and lies within the midgate is accepted as an echo from a midline structure. Midechoes are accepted only from within a distance of 20% to either side of the true centerline of the head. For example, for a patient with a temporoparietal head diameter of 150 mm, the midgate width is 30 mm. Thus, no echo displacement greater than ±15 mm will be displayed. This range was felt to be adequate, since shifts of greater than 1.5 cm rarely occur in the region in which the measurement is commonly made (area of the posterior third ventricle). If an echo group of a characteristic midpattern is received, the difference between its distance, M, and the midhead distance, D/2, is computed automatically and displayed, in millimeters, as a shift right or left of the centerline. At the same time, a 500 Hz audio tone is generated to inform the operator that the determination has been completed. Both the tone and the digit illumination remain until manually reset.

If an acceptable midecho pattern is not received within the same 2 msec period as the distal, the whole memory is erased and the total determination begins again. The brevity of this total search period insures that the midline measurement will always be normalized to the distal echoes, since probe movement in 2 msec could not possibly cause significant relative misalignment of the mid and distal echoes.

As the location of each midecho is registered on the digital display, it is plotted manually in the form of a histogram on a data sheet ruled at the same intervals as the display and placed below it. In most cases, only 10 to 15 echoes need to be obtained. If most of these are indicated as "0" or 2 to 4 mm to the right or left of "0", the normal location of a midstructure is established. The accumulation of data points need be carried only so far as required to obtain a well-local-

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Fig. 2. Histogram of an adult patient with a normal midline.
ized, statistically significant echo pattern since, as mentioned earlier, the sole purpose of this device is to locate the midecho complex. Figures 2 and 3 show typical bar graphs from a normal patient and from one with a midline shift. Histograms containing 20 to 30 points, such as these, are usually obtained in about 5 minutes. The measurements made from the right side of the head were recorded with "X" marks; those from the left side with dots; extending the bars produced the combined solid-line histogram. Either one or both sides of the head may be used. The ability to perform the measurement from one side only is of particular value in following patients after a craniotomy.

Although a single power level can be used in the majority of patients, it was found necessary to provide a control to increase or decrease power input by a factor of 1 for successful measurement in patients with very thick or thin skulls, respectively. Failure to complete the distal search (absence of 250 Hz tone) signifies an inadequate power level. An overload of echoes caused by an excessively high power input is indicated by a red light near the power control.

Several points should be made regarding the distribution shown in Figure 2:

1. The display magnifies the midline region by a factor of 5, as indicated by the 1:1 scale graph at the top of the data columns.
2. There is a significant group of echoes located approximately on the centerline of the head. The peaks from each side of the head are centered 1 to 2 mm proximal to the detector, partially due to the natural width of the normal midline structures (3 to 6 mm) and to the fact that distances are computed from the leading edge of the first acceptable midline echo received.
3. Echoes from surfaces other than those of midline structures can be noted and, in many instances, are not readily
A computerized echoencephalograph identifiable by either the computer or oscilloscopic examination. If one of these had been the only recorded measurement, a false positive diagnosis would have resulted. However, the acquisition and plotting of multiple echo locations make it possible to put such values in context and to estimate, to some extent, the spread of the distribution. In addition, some reverberation echoes from the near side of the skull, which usually occur at the outer limits of the gate, occasionally appear on the side of the head toward the probe.

A pattern may be detectable only, or more easily, from one side of the head, or distinctly different peaks may be found from opposite sides. The presence of more than one group may supply significant additional information (e.g., enlarged third or lateral ventricles) and may stimulate further diagnostic tests. However, it is important to emphasize again that this instrument is particularly designed for the localization of a midstructure complex. In general, if a significant shift exists, it will be clearly indicated, as in Fig. 3. In our experience, in approximately 10% of all cases the echoencephalographic technique will fail to detect satisfactory midstructure echo patterns. A significant number of failures have occurred in patients proven by radiological studies to have midline shifts resulting from intracranial mass lesions. Gross distortion of midline inter-spatces preventing adequate back-echo generation is a logical explanation for failure of the technique in such patients. Depending, of course, on the clinical circumstances, failure to detect midstructure echoes in a patient may, therefore, be in itself an indication for other diagnostic techniques.

One of the basic considerations in the design was to simplify the instrument operation to such an extent that the only decision required would be in the power level used. The front panel of the hand portable unit* is shown in Fig. 4. The millimeter digit lamps are arranged in a linear array to minimize transpositional and transcriptional errors on the part of the operator. A reference standard has been constructed which simulates the brain and skull interfaces and offers a verification of the complete search circuits and computational logic.

Acknowledgments

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