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BIOMEDICAL APPLICATIONS OF A COMMERCIAL CAPACITANCE TRANSDUCER

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I. Introduction

The detection and measurement of chest wall motions have been investigated in the past, using many different transducers (1, 2, 3, 4, 6, 7). These transducers can be divided into two groups—contacting and noncontacting. Experience is greatest using contacting transducers of various types (piezo-electric crystals, condenser microphones, carbon microphones, etc.). The problems inherent in these methods include the lack of DC response, lack of a linear response proportional to distance and distortion of the measurement due to contact.

In order to overcome these problems, noncontacting transducers have been developed using body capacitance (4) and photo-electric detection of light reflected from the vibrating surface (6). Again, linear response proportional to distance has been a problem with these devices. Berson and Pipberger reported a photo-electric method that detects the motion of a light-weight target riding on the chest (3).

Excellent reviews of the past methods in this area have been made by Groom (7), and Berson and Pipberger (3) have reviewed the instrumentation used and the problems of transducer design.

It is the purpose of this paper to report the use of a new commercially available noncontacting capacitive transducer* which produces a linear output proportional to distance and has a frequency response from DC to 10 KHz.

II. Principle of Operation

The design is centered on a high-gain feedback amplifier. An input reference signal consists of the current passed by a standard capacitor connected to a 50 KHz oscillator. A feedback loop is completed by the capacitance formed between a probe and the structure under test, and feeds a current to the amplifier input in opposition to the reference signal. The amplifier output voltage is therefore inversely proportional to the probe/structure capacitance and this, in turn, is inversely proportional to the probe/structure separation. Hence, the 50 KHz output from the amplifier has a mean amplitude determined by the mean distance between the probe and test structure, and is amplitude-modulated to an extent depending on the peak-to-peak vibration of the structure. A feedback voltmeter rectifies the 50 KHz signal and indicates mean distance. A simplified schematic is shown in Figure 1. A more detailed circuit analysis is given in Appendix A.

III. Verification for Use in Physiological Measurements

Although this device produces a linear output using flat metal surfaces, it had to be shown that its use can be extended to chest wall and pulse measurements. Under these conditions one side of the capacitor is skin which may have a curvature. Two sets of measurements were made to determine linearity when (1) skin is used as one side of the capacitor and when (2) curved surfaces are used.

To verify the use of this transducer on skin surfaces the probe surface was placed parallel to the skin on a finger which had been taped to a table top. The movement of the probe was monitored by means of a dial gauge. The probe separation as read on the distance meter and the dial gauge were both adjusted to read 0.100 inches and increments of about 0.010 inches were made as shown in Figure 2.

A second series of measurements were made to determine the effect of curved surfaces on the linearity. To do this the measurements were again referenced to the dial gauge and metal curved and flat surfaces were used as one plate of the capacitor. The results in Figure 3 show the response for the various surfaces with maximum deviation again at the small separation.

*B731A Vibration Meter, Southfield Electronic Sales, Inc. 21250 10½ Mile Road Southfield, Michigan 48075.

These tests verify the use of this device for this application. The obvious lack of any loading feedback to the motion under study is assured because of the non-contacting feature. High magnetic fields had no measurable effect on the device's performance.

IV. Dynamic Characteristics

The frequency response characteristics were determined at the U.S. Navy Ship Research and Development Center in Washington, D.C., using their shake tables. The results of this test are shown in Figure 4. The motion of the top of a calibrated accelerometer mounted on the shake tables was monitored and based on its calibration, the peak-to-peak displacement was calculated. In order to determine that the top of the accelerometer followed the motion of the table, a measurement to the table was made at 700 Hz as shown in the figure. The fall off of the response at the high end is due to a 1,000 Hz low-pass filter used in the output circuit of the vibration meter, and the low-end calibration was limited by the frequency characteristics of the shake table itself.

V. Results

The major applications of this device investigated thus far have been measurements of chest wall motion at the apex, point of maximum precordial impulse (apexcardiogram). A typical apexcardiogram (ACG) taken with a piezoelectric transducer is shown in Fig. 5, where the ACG, carotid pulse and phono were taken with conventional transducers. A displacement apexcardiogram of the same subject taken with the capacitance device is shown in Fig. 7 along with its first and second derivatives. Brachial arterial pulses (capacitance transducer) are shown in Fig. 6. No difficulty was experienced in measuring vessel pulses in both the brachial and radial arteries. Good results are dependent largely on patient cooperation and experience in placement of the probe.

Because of wide dynamic range and frequency response, it is possible to place the probe at the apex and with the subject breathing obtain a respiration tracing with a small variation superimposed on it (the apexcardiogram). Then by having the subject hold his breath and then increasing the gain of our recorder we could magnify this apexcardiogram and eliminate the curve of respiration. Also, with and without breathing depending on the range of the probe, low frequencies could be filtered out and heart sounds obtained.

The extended range and frequency response allowed electronic differentiation of the apex and brachial displacements for velocity and acceleration of the motion. An example of this is presented in Figure 7 and a comparison between acceleration made in this way and directly, using a sensitive miniature accelerometer* coupled to a special calibrated amplifier† is shown in Figure 8.

VI. Discussion

Because this distance measurement requires the use of a disk capacitor plate rather than a point, the measurement inherently has some "averaging" of information. That the apex motion does not move so as to maintain a parallel relationship with this capacitor disk is also reason to expect some distance averaging. Exactly what this effect does to the frequency response and accuracy of the measurement must be investigated further or determined.

Hazards Involved

Subjects have occasionally reported burning sensations at the leg electrode (used for ground return) when other instruments such as on ECG were attached. The use of telemetry circumvented this problem.

When the instrument is used alone and with the probe making firm contact on the dry chest wall a burning sensation has been reported at the probe end. A thin plastic or rubber film has been wrapped around the probe and use successfully, i.e., with the probe making firm contact with the chest wall, no subject has ever reported any sensation or shock. However, the transducer must be recalibrated because of the additional dielectric material added.

Peak-to-peak voltage (guard ring to ground) and current measurement* (10 ohms in series with the guard ring circuit at the probe end) have been made for two conditions of the probe and three conditions of the test procedure for determining the hazard involved. The probe was used "uncovered" and "covered" with a thin

*Wilcoxon Accelerometer, Model 137.

†Ithaco Amplifier, Model 252.

*Tektronix 555 Scope, Type D Input, 1 Meg. Shunted 47 $\mu\mu$f.

rubber film. Using a subject and with the probe open-circuited (not on scale) 60 volts and 350 ma. was read, rubber covered; and 52 volts and 350 ma. with the probe uncovered. Under normal test conditions with the probe not touching (0.4 meter reading) 5.2 volts and 36 ma. was read, rubber, covered; and 5.2 volts and 36 ma., uncovered. With the probe making firm contact with the chest wall 6.4 volts and 40 ma. was read, rubber covered; and 1 volt and 66 ma. uncovered and not motorboating. Under this condition of touching the subject with the probe rubber covered and uncovered, the carrier frequency shifts from the 50 KHz normal operating frequency to 178 KHz. In addition, with the probe uncovered, and touching the subject, an unstable condition occurs in which the instrument starts motorboating at 6.6 Hz, 6 volts and 90 ma. is read and a shock is reported.

It must be pointed out that this instrument was designed for industrial applications. Its use in this study was primarily for research purposes and in the hands of inexperienced or untutored personnel, this device may be hazardous, particularly if the subject or patient is also connected to other medical instrumentation.

VII. Summary

We have described a capacitive displacement transducer with a linear response and constant sensitivity for a frequency range of 0–1,000 Hz. Its application to measurement of chest wall motions was verified using static displacements from flat and curved surfaces and both metal and human tissue.

The transducer has been used to obtain recordings of apex motion, heart sounds, brachial and radial pulses.

Its advantages are that it is noncontacting and linear; that it has a wide frequency response and can easily be calibrated to obtain quantitation of actual motion.

Problems encountered in use were the mechanical positioning of the probe including respiratory motions in the measurement and the need to insulate the probe with a film of thin plastic to insure against any electrical hazards to the subject.

Appendix A

See Fig. 1.

WHERE:

V_1 = Source potential.

V_o = Amplifier output.

R = Grid resistor of amplifier input stage.

C_s = Standard capacitance (of reactance X_s).

C_u = Probe/structure capacitance (unknown, of reactance X_u).

i_1 = Current passed by Standard.

i_2 = Current fed back by probe capacitance structure.

e = Potential across R.

A = Amplifier gain.

THEN:

$V_0 = A \cdot e$ and $e = (i_1 - i_2) \cdot R$.

$A >> 1$ and C_u is comparable with C_s.

THEREFORE:

$e \to 0$ and hence, for finite R, $(i_1 - i_2) \to 0$, that is, $i_1 = i_2$.

NOW:

$V_0 = i_2 \cdot X_U$ (if $e = 0$).

AND:

$V_1 = i_1 \cdot X_S$ (if $e = 0$).

$$\frac{V_0}{V_1} = \frac{i_2}{i_1} \cdot \frac{X_u}{X_s}$$

BUT:

$i_1 = i_2 \therefore V_0 = V_1 \cdot \frac{X_u}{X_s}$

BUT:

V_1 and X_s are constant.

PUTTING:

K for V_1/X_S, $V_0 = K \cdot X_U$.

NOW:

$X_u = \frac{1}{wC_u}$ and $C_u \propto 1/d$, where d is the plate separation.

$V_o = K'd$ where K' is a new constant of proportionality.

The amplifier output (V_o) is thus directly proportional to the probe/structure separation (d) and is independent of the amplifier gain.

Appendix B

Range of Probes:

Six probes are available for use with the instrument. The standard probes have a flat, circular inner electrode surrounded by a guard ring. The electrode and guard ring are separated by an insulating sleeve. The probes are screwed into a probe holder mounted on the end of a coaxial cable.

The range of the probes for the instrument is:

Probe	*Effective probe radius*	*Normal FSD (Distance and Vibration)*	
	Inches	*Inches*	*Millimeters*
A	0.0223	0.001	0.025
B	0.050	0.005	0.125
C	0.0707	0.010	0.25
D	0.158	0.050	1.25
E	0.223	0.100	2.50
F	0.500	0.500	12.5

It should be noted that full scale deflection (FSD) of the meter corresponds to 1 volt at the output of the filter. Therefore, the sensitivity for the F Probe is 1 volt per 0.500 inches or 2 volts per inch deflection over the range of the probe, i.e., 0 to 0.500 inches. The sensitivity for the D Probe, one particularly useful for chest wall motions (apexcardiograms), is 1 volt per 0.050 inches or 20 volts per inch over the range 0 to 0.050 inches.

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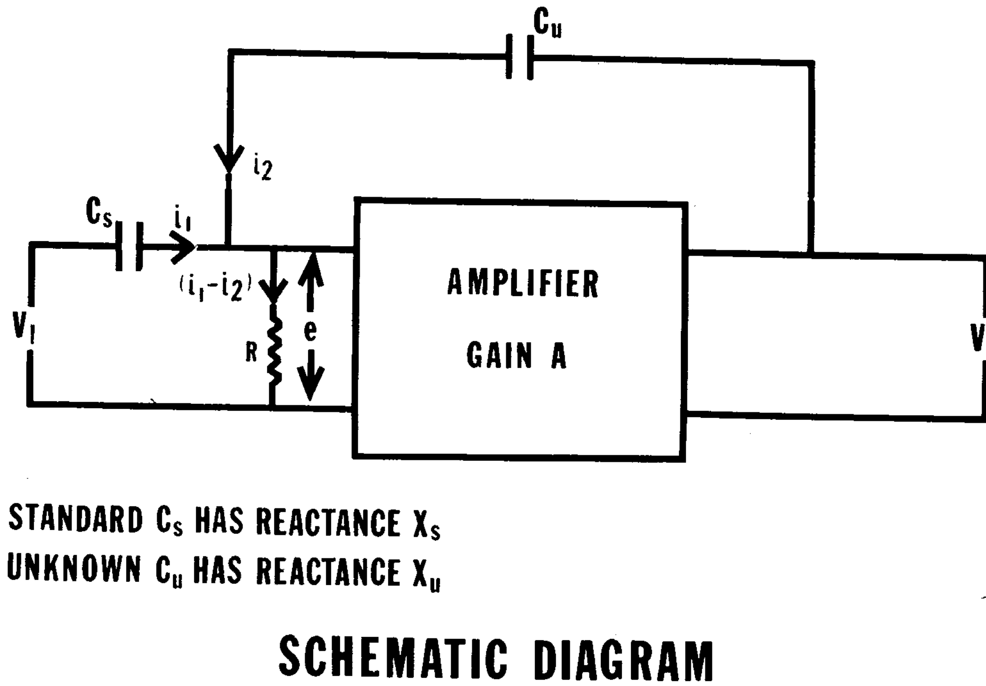

FIGURE 1. Simplified schematic diagram.

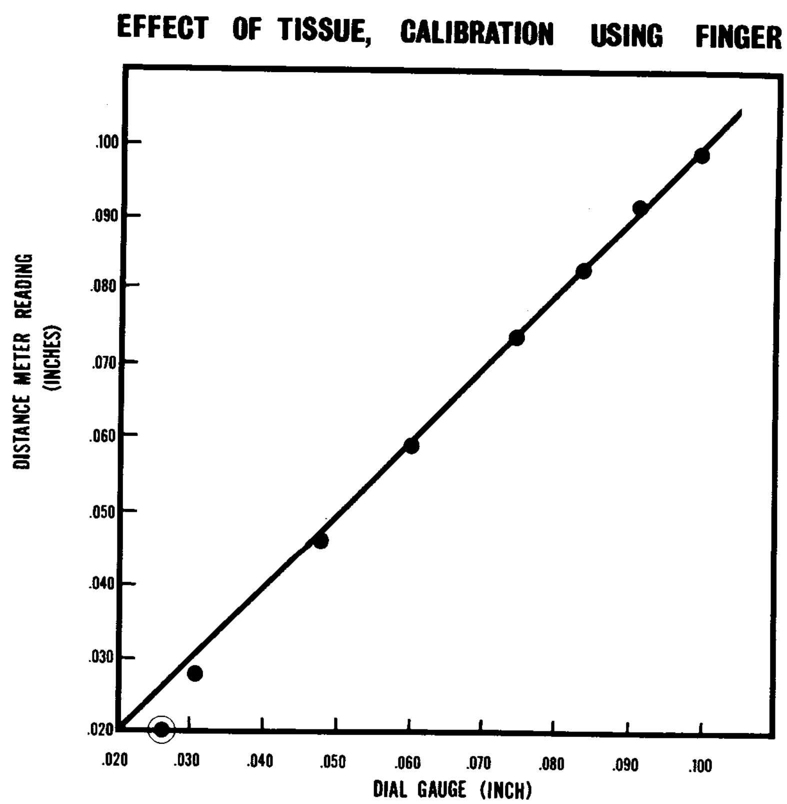

FIGURE 2. Effect of tissue, calibration using finger.

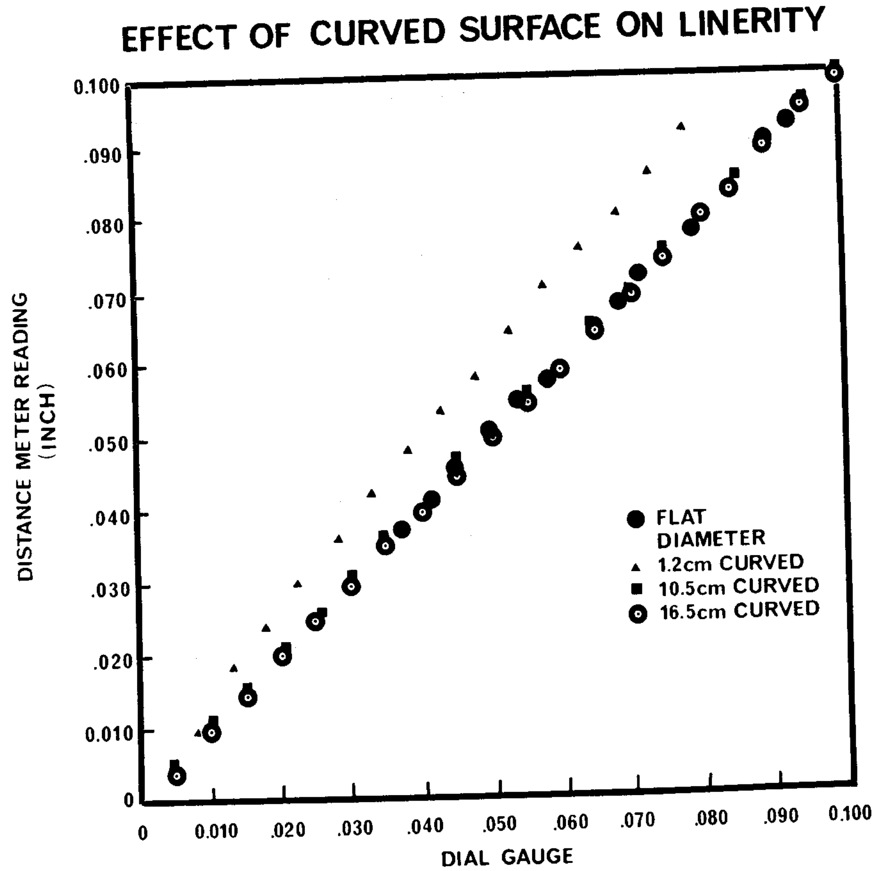

FIGURE 3. Effect of curved surface on linearity.

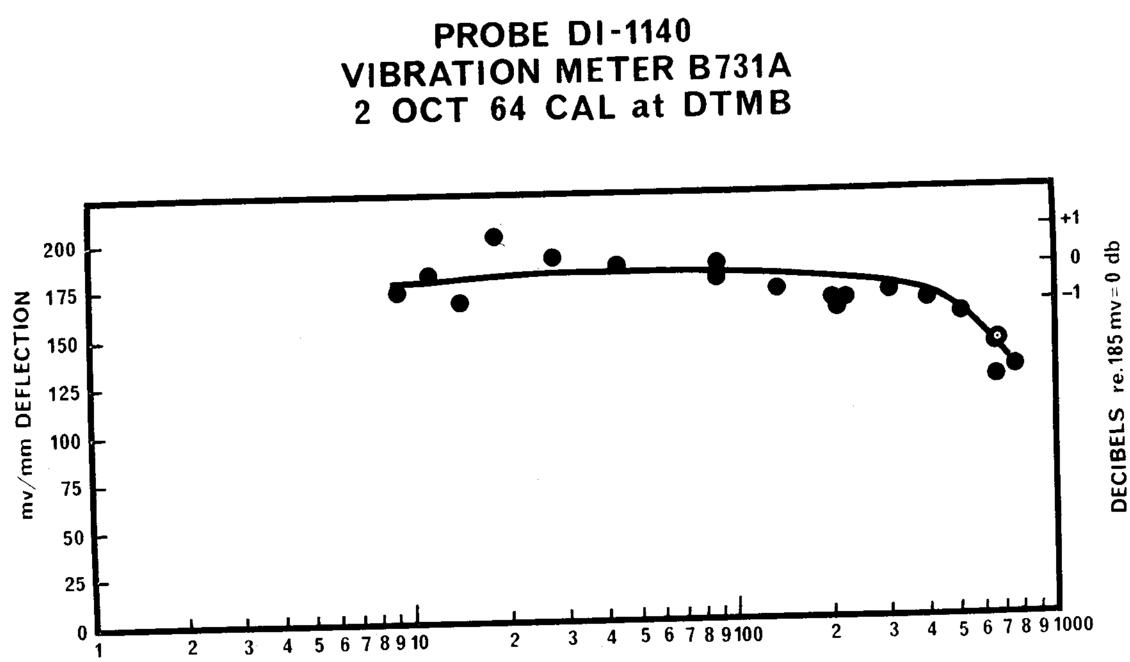

FIGURE 4. Frequency response characteristics.

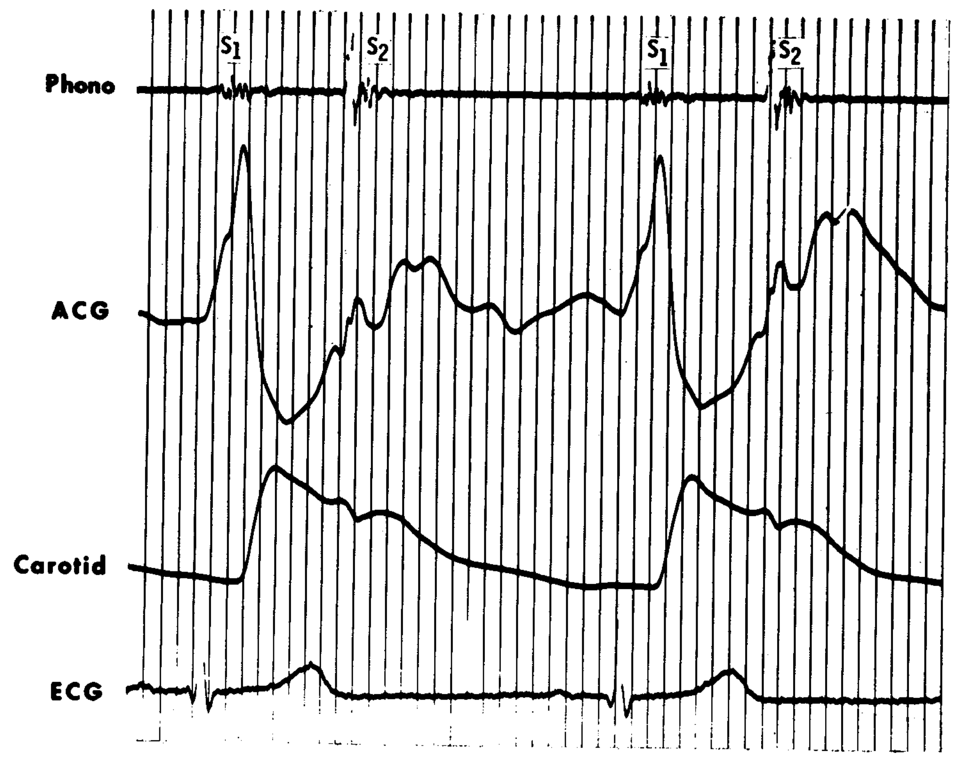

FIGURE 5. An apexcardiogram (ACG) taken with a conventional piezoelectric transducer. ECG, Carotid and Phono taken with conventional tranducers.

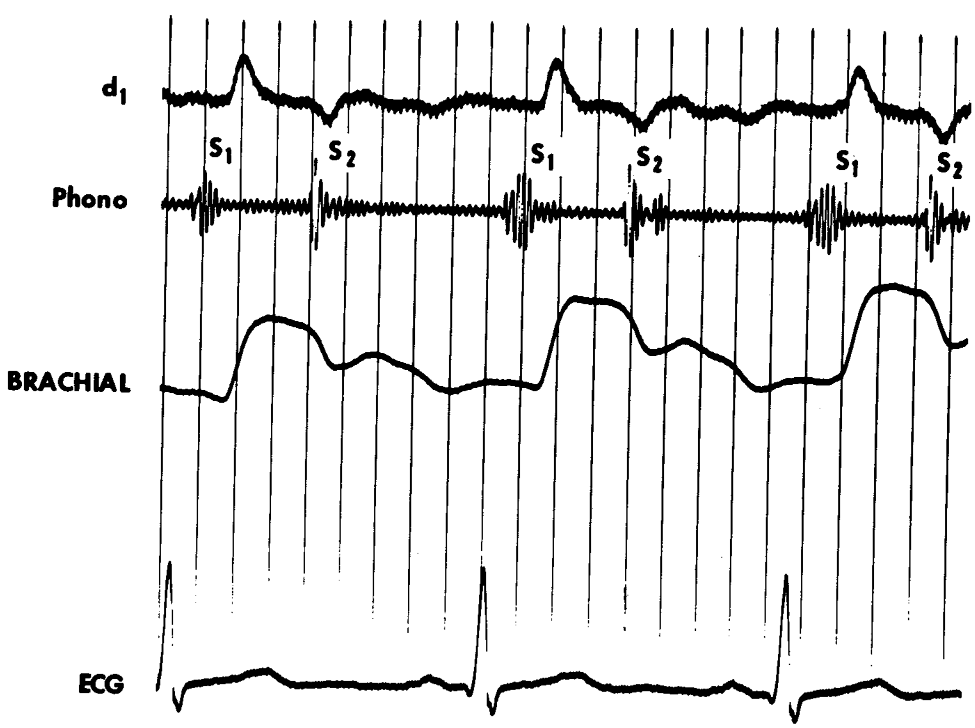

FIGURE 6. Brachial artery pulse and its derivative d_1. Phono taken by piezo-electric transducer.

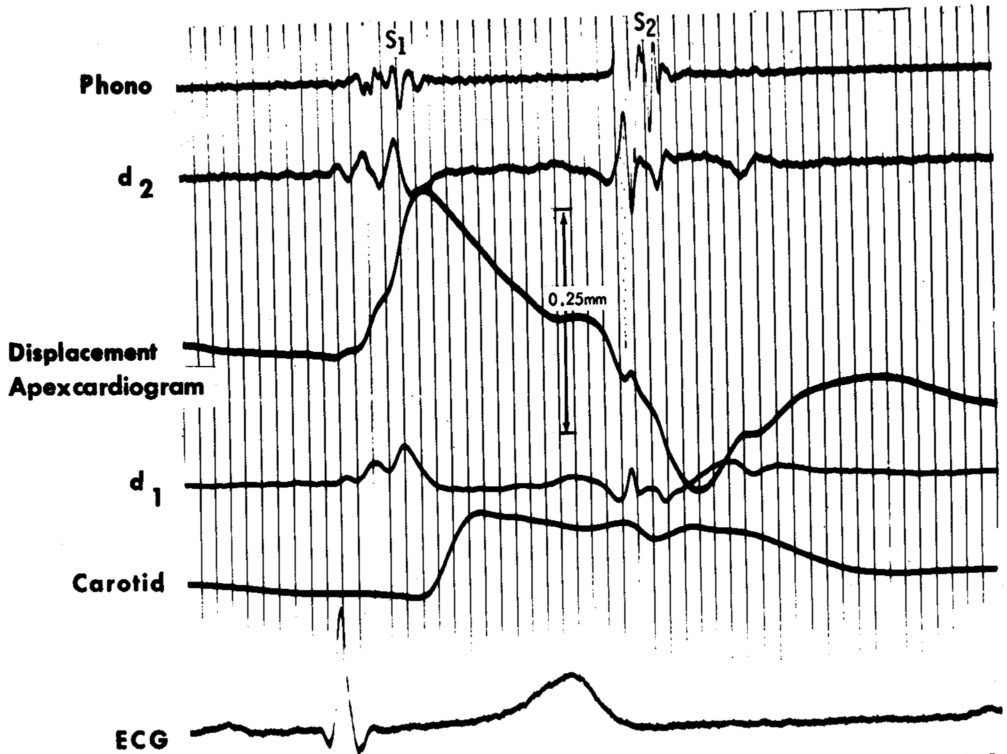

FIGURE 7. A displacement apexcardiogram (capacitance transducer) with its first d_1 and second d_2 derivatives. The carotid pulse and phono taken with conventional transducers.

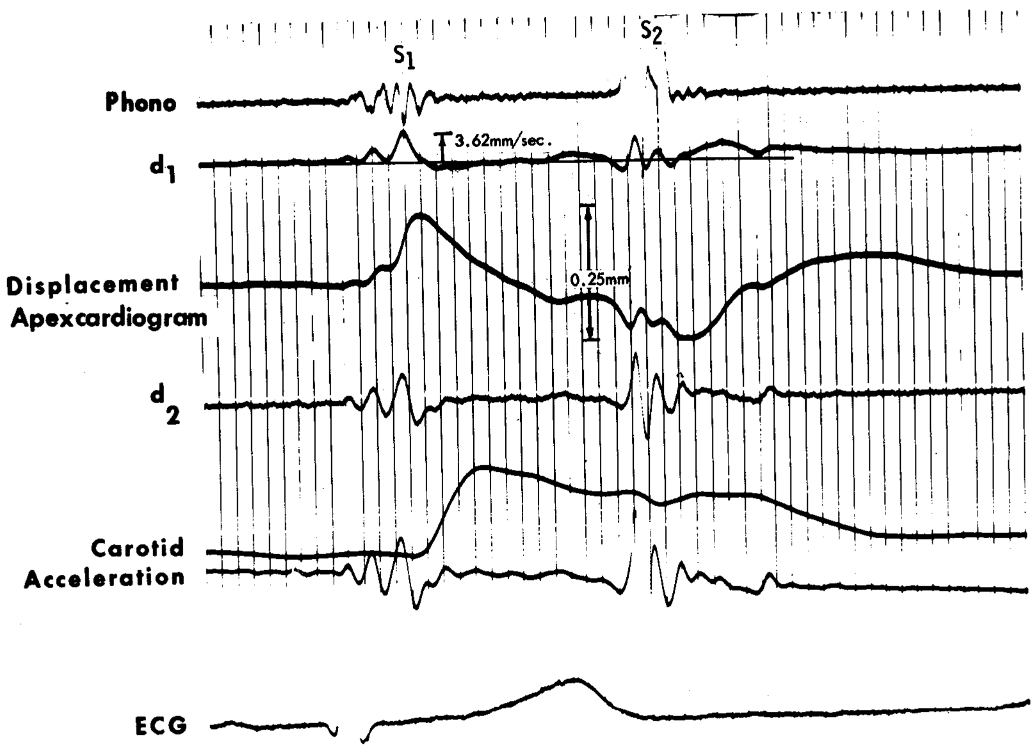

FIGURE 8. Comparison of the second derivative d_2 of the displacement apexcardiogram with the accelerometer output.

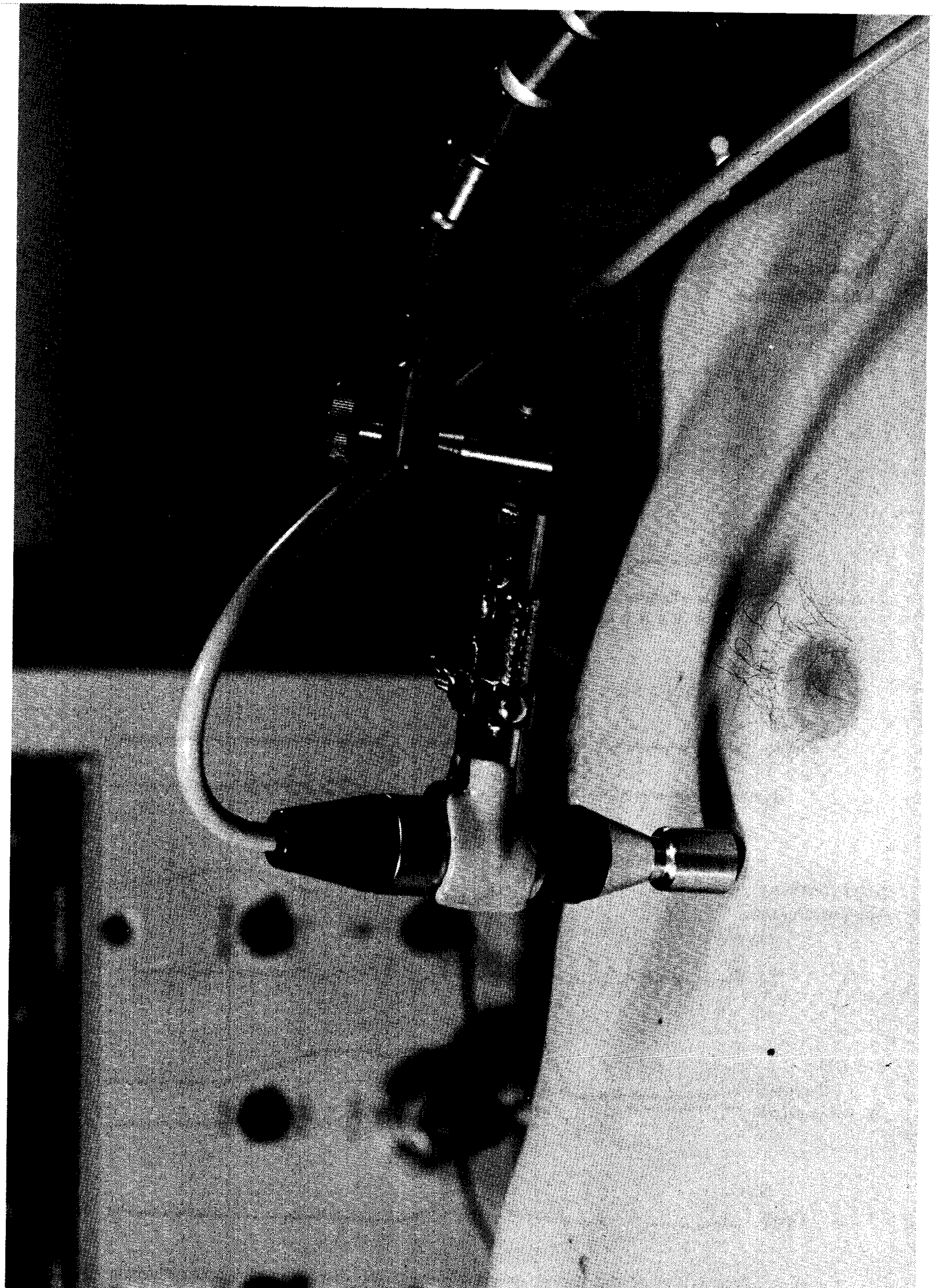

FIGURE 9. Probe shown in use.