Air Leaks as a Source of Distortion in Apexcardiography


Small air leaks have been observed to be frequently present in a popular crystal transducer and to cause significant distortion of the apexcardiogram. Such leaks introduce a short time constant thereby differentiating the wave form and producing: (1) peaked and amplified A waves; (2) early fall off of the systolic wave; (3) increase in slope and relative duration of the rapid filling wave. Leaking was found to develop at the seal between the transducer housing and a gasket and was easily eliminated with the application of silicone lubricant. A test “square wave” was produced by quickly clamping the tube connection from bell to transducer, and a short time constant thereby observed as a clue to the presence of leaking. The possibility of such leaks and of certain other physical limitations discussed in this paper support the need for a new device which can simultaneously reproduce the phonocardiogram and apexcardiogram.

External recordings of apical movements have been used increasingly in recent years for timing of cardiac events and for the diagnosis of abnormalities of cardiac function. Among several techniques available for these purposes the apexcardiogram is popular because of its simplicity in use.

In recent years investigators including Benchimol and Dimond,¹ Coulshed and Epstein,² J. S. Fleming and Hamer,³,⁴ J. W. Fleming,⁵ Tafur and co-workers,⁶ Tavel and associates,⁷,⁸ and others have described the usefulness of apexcardiography in many clinical states. These authors have outlined the method of obtaining reproducible records and have shown the artifacts which improper technique can induce.⁵,⁸,¹²

However, although warnings have been raised, little specific attention has been paid to the problem of time-constant variation induced by small air leaks in the recording equipment. We have observed this technical imperfection quite commonly and have devised methods to detect its presence so as to eliminate a significant source of signal distortion.

In this report we shall describe the nature of the problem, discuss a method for its detection and finally consider the construction of an ideal apexcardiographic recording device.

Methods and Results

Equipment

Many apexcardiograms are recorded with a crystal microphone which converts pressure changes into electrical signals. The microphone frequently employed for this purpose is manufactured by Sanborn Company, now a division of Hewlett-Packard Company, Waltham, Massachusetts (Fig 1). This instrument was first described in 1941 by Miller and White¹³ and early clinical records of use of the technique were published by Rappaport and Sprague¹⁴ (Addendum 1).

The transducing element of the microphone is a piezoelectric crystal which has the property of generating an electric voltage when twisted or squeezed; the magnitude of the voltage is proportional to the applied force. The electrical energy is led off the crystal by thin metal foil electrodes.
cemented to opposite faces of the crystal. The wires from this crystal lead to a box which contains a resistor and capacitor, the function of which will be explained below. The electrical output of the crystal is then amplified and either photographically or mechanically recorded.

The tracings for this study were amplified and recorded on a Sanborn (Hewlett-Packard) series 580 unit which includes 350-3200A preamplifiers for apex and electrocardiography and 350-17000A preamplifiers for phonocardiography.

**Air-Tight Coupling Circuit**

At the “front end” of the recording assembly is an air-tight coupling between the skin of the patient’s chest and the microphone assembly. The mechanical movement of the apex is transmitted as a pressure wave in air, first through the cone which is applied to the chest then via a rubber or plastic tube to the piezoelectric sensor itself. It is clear that an air leak in this circuit could distort the signal before it has been converted into electrical information. We were surprised to find that such air leaks are commonly and easily produced and that their distortion may be great though their magnitude be small.

Our attention was directed to this problem when a crystal assembly was inspected to learn why the reproduced signal decreased rapidly when a steady “square wave” of pressure was introduced into the microphone. A small leak was noted at the seal between the crystal unit itself and its housing (Fig 2). When the assembly was made air-tight, signal reproducibility returned to satisfactory levels.

**Artificial Production of Leaks**

In order to study the nature of this artifact, a controlled leak was introduced into the pneumatic circuit of a previously nonleaking unit. The rubber tubing between the pick-up cone on the patient’s chest and the crystal microphone was cut and a thick-walled metal tube inserted. Into this metal tube was drilled a small hole 5 mm long and 0.325 mm in diameter (Fig 3). By uncovering the hole, a leak with known properties could be introduced at will. Apex recordings were then made on patients with various forms of heart disease in end expiration in the left lateral position with and without leaking. The artifacts induced by leaks can be clearly seen (Fig 4-6).

**Testing for Leaks**

A convenient method was devised to test whether the Sanborn No. 374 crystal microphone assembly was leaking. A satisfactory test wave was introduced by quickly compressing with a clamp the rubber tubing attached to the microphone. A small amount of air was displaced and the crystal perceived this as a square wave. When a leak was present the reproduced wave form rapidly decreased and upon release of the clamp, air rushed back into the circuit and a negative deflection was produced. If no leak was present between the clamp and the microphone, the deflection decreased more slowly at a rate determined by the overall time constant of the electronic circuit (Fig 7).

**DISCUSSION**

Palpation of the precordial cardiac impulse is a
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These variations in apical records are caused by several factors, some deliberately introduced and others present by accident and not by design. In order to analyze these differences, we may refer to a schematic diagram which shows the steps through which the heart's motion is processed in such studies. This chain of biological, physical and electromechanical components is illustrated in the block diagram (Fig 8).

Transmission Through Body to Chest Wall

The transmission of the apex movement from the heart to the surface of the skin is a complex process. The intervening tissues including the pericardium and its fluid contents, muscle, fat, connective tissue and bone all affect the passage of the characteristic low-frequency pulses that constitute the apex displacement. The anatomical changes produced by thoracotomy without removal of a rib can also change the impulse. Inability to make a good recording is also all too frequently due to abnormalities of the chest wall.

Coupling from Body to Transducer

Motion of the body surface at the cardiac apex can be defined in two general ways. If the sensing device is secured to the bed or to a stand, the tracings obtained reflect heart motion within the chest, plus any movement of the chest wall itself, with respect to the fixed external point. The kinetocardiogram of Eddleman and his associates\textsuperscript{16} and the
FIGURE 7. The effect of air leaks on the time constant of a transducer. These illustrations have been taken directly from the photographic record produced by the transducer and amplifier. Time lines are automatically inserted by the recorder and vary appropriately according to the paper speed.

Top: A “square wave” of pressure has been introduced by compressing the flexible tubing attached to a non-leaking transducer with a clamp. The recorded signal falls off gradually reaching its time constant \(1/e=37\) percent in 2.1 sec. Most of this decay is a function of the AC amplifier conventionally used with such instruments.

Bottom Left: The same test was applied to a crystal transducer with a small air leak. Note the short time constant of only 90 msec. Such distortion of the low frequency signals produces characteristic changes in the apexcardiogram.

Bottom Right: The small leak introduced by the metal tube (Fig 3) has a similar slightly shorter time constant. The variations in the form of the apexcardiogram produced by the leaking transducer or by the metal tube are virtually identical.

FIGURE 8. Schematic diagram illustrating some of the processes employed in the conversion of cardiac apical movement into the apexcardiogram (for details see Discussion).

impulse cardiogram of Mounsey and his co-workers\textsuperscript{17} provide such records. In apexcardiography, on the other hand, the sensing device is either secured to the chest wall with a strap or held in place by hand. The device moves with the chest wall, so that the movement of apex with respect to the adjacent chest areas is recorded.

Size of pick-up: Difference in the form of the recording is also introduced by the size of the pick-up applied to the chest. Nixon\textsuperscript{18} and others have mentioned and Bancroft and Eddleman\textsuperscript{16} have illustrated the changes in pulse contour produced when the contact area is changed. For example, a record made from nearby but not on the apex may be inverted.\textsuperscript{9} Hence recordings centered at the apex but including surrounding areas will be different from the impulses taken at the apex alone.

One of the most useful features of the Sanborn assembly is its ability to permit recording of simultaneous sound and apex displacement. However, the cup which fits against the chest wall has a two-inch diameter (Fig 1) and consequently movement surrounding the apex is incorporated into the record. Two considerations make this arrangement less than ideal. First, the apex record is not a true reflection of what the observer perceives in palpating the apex itself; and second, the use of instruments with different size pick-ups causes confusion in developing standards for precordial displacement. (Our further studies of this problem will be reported separately.)

Air leaks: The investigation reported here may also be considered under the heading of body-transducer coupling. For the air leaks observed distort the apical record before conversion into electrical information has been accomplished. The effect of leaks is to shorten the time constant of the system, thereby differentiating the wave form.

The concept of time constant is not difficult to understand as it applies to the reproduction of pulse waves and apical impulse recordings.\textsuperscript{5,19} A
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Figure 9. Interior of the “gray box” which connects the crystal transducer to the amplifier input. The 1 microfarad condenser (top) and 22 megohm resistor form an R-C circuit which prolongs the intrinsically short time constant of the crystal itself. This arrangement, however, markedly decreases the output from the crystal and a high-gain AC amplifier is needed for further processing of the signal. Such AC amplifiers shorten the time constant produced by the transducer and its R-C circuit as illustrated in Figure 7, but the result is satisfactory for most clinical purposes in recording of precordial movements.

Although time constant measurements are usually applied to electrical circuits, the same mathematical expressions can be derived for an acoustical system such as the pneumatic coupling arrangement discussed above (Addendum 2).

A short time constant circuit, either electrical or pneumatic, may also be considered as a differentiating circuit. Differentiation accentuates the rapidly changing segments of a pulse as in the conversion of a square wave into a pair of biphasic spikes. Whether this differentiation is produced electrically by a short RC circuit or by an air leak in a pneumatic circuit, the results are quite similar.

The air leak we introduce is very small; nevertheless, its effects are significant and predictable: (1) the A wave becomes more peaked and higher relative to th E - O vertical distance; (2) the systolic wave falls off shortly after the E point and does not maintain its expected upward or level excursion; (3) the slope of the rapid filling wave is more steep and its vertical interval relatively longer.

Perhaps such leaks contribute to the different records obtained by Dimond10 from the Sanborn and from other types of transducers. He observed that the Sanborn No. 374 instrument “did not consistently give a flat response in the very low frequency range (0.1 to 4 cps),” and it is within this range that most of the useful information in apexcardiography is produced. An air leak would distort in particular these low frequency components.

![Diagram](http://journal.publications.chestnet.org/pdfaccess.ashx?url=/data/journals/chest/21488/)

Figure 10. Equivalent electrical circuit for the acoustic and mechanical elements of an apex cardiograph recording system.

ACOUSTIC COUPLING  PIEZOELECTRIC TRANSUDER  COUPLING BOX  AMPLIFIER RECORDER

\[ p = \text{pres. pulse of skin surface} \]
\[ C_a = \text{acoustic cap of cup} \]
\[ C_d = \text{acoustic cap of diaphragm} \]
\[ R_L = \text{leakage resistance} \]
\[ v = \text{volume flow} \]
\[ I = \text{current output} \]
\[ E = \text{voltage pulse} \]
\[ C_x = \text{capacitance of crystal} \]
\[ C_b = \text{loading capacitor} \]
\[ R_b = \text{bleeder resistor} \]
\[ C_g = \text{effective capacitance} \]
\[ R_g = \text{effective resistance} \]

\[ T_a = R_L (C_a + C_d) \]
\[ T_x = R_b (C_x + C_b) \]
\[ T_g = R_g C_g \]
**Pressure Pulse Transducer**

Even with an intact nonleaking pneumatic circuit, the form of the apex record may be significantly affected by the time constant of the transducer itself. A pulse wave transducer, such as the Sanborn No. 374 consists of a piezoelectric crystal element which generates an electric potential under mechanical stimulation.* The voltage is briefly stored on the metal foil electrodes attached to the crystal and then discharges across a resistor located in the small box attached to the plug which fits into the amplifier (Fig 9). The crystal and its foil electrodes constitute a capacitor and together with the resistor form an RC circuit whose time constant is very short. In order to lengthen it another capacitor is introduced in the coupling box which increases the inherent capacitance of the crystal.

The time constant of this circuit is in excess of 20 seconds. Since systole seldom occupies more than 0.3 second, for all practical purposes a reliable wave form will be reproduced.

Another method of increasing the effective transducer time constant is to add a preamplifier with a very high input resistance. Such an arrangement has been described by Roberts and Sherwood Jones, who employed an electrometer tube for this purpose. Such circuits, however, are not commonly available in commercial equipment.

Actually, transducers are available which will generate an impulse with an infinite time constant, although the advantage of this feature for clinical purposes is minimal. Such instruments include: (1) Phillips inductive displacement transducer type PR9310**, (2) modified Statham transducer UC3; (3) Hewlett-Packard displacement transducer APT16. Another type of “leak” should be mentioned at this point. It has been suggested that the entrance of moisture into the crystal assembly will cause an “electrical leak” and thus shorten the time constant of the transducer itself. The presence of this type of “leak” may also be detected by the method described for air leaks.

**Electrical Amplification**

In Figure 7 we see that despite the use of a nonleaking crystal transducer with a time constant of over 20 seconds, the input square wave regresses to about 37 percent of the initial amplitude in 2.1 seconds. This shortened time constant is produced for the most part by the electrocardiographic amplifier commonly used for pulse recording. Such amplifiers are designed for the relatively low signal input of an ECG and the time constant is quite adequate for reproduction of the higher frequency electrocardiographic signal. However, even a 2.1-second time constant is satisfactory for apex recording since this is approximately eight times the duration of systole. Some distortion is present, but it is minimal.

Even this limitation can be eliminated, for amplifiers as well as transducers with infinite time constants are available. However, DC (infinite time constant) amplifiers are not commonly used. In providing extended frequency range such circuits introduce certain undesirable features such as signal drift and low frequency interference. Hence at this time, crystal transducers are conventionally fed into relatively high gain AC amplifiers with limited time constants.

**Recorder**

The final block (Fig 8) shows that after amplification the signal is converted into an optical image or recorded directly by a stylus onto paper. The principal disadvantage of direct-writing, commonly employed in electrocardiography is that the mechanical movement of the writer is limited by inertia, thus distorting the higher frequency components. However, for the frequency range used with apexcardiography, direct-writing instruments are quite adequate in technical performance and more convenient in clinical use. Their limitation is more evident with phonocardiography.

**“Ideal” System**

The popular air-coupled crystal transducer still has a place in apexcardiography despite the limitations discussed above. It is the most familiar device used for recording in conjunction with a sound microphone. However, we believe that a new device is needed which will permit simultaneous apex and phono records to be made without the distortion introduced by leaks, time constant limitations, and such factors as the effect of the surrounding chest movement.

Nixon, Hepburn and Ikram have constructed such a unit which consists of a DC transducer for the apex impulse combined in a plastic housing with a sound microphone. This arrangement is an ingenious step on the way toward a single pick-up device which can serve both needs.

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*The Sanborn model No. 374 pulse wave pick-up has been superseded by Hewlett-Packard model No. 2105A pulse wave transducer. This new unit is essentially unchanged from the No. 374 model except that the Rochelle salt crystal has been replaced by a ceramic piezoelectric element. This modification has the advantages of better temperature stability and increased output.

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The requirements for such an ideal instrument are fairly simple to outline. The contact area must be sufficiently small to eliminate the influence of movements near but not at the apex; the time constant must be sufficiently long to reproduce the movements near but not at the apex; the time constant must be sufficiently high so that the phonocardiogram will be accurate. Theoretically, it is possible to construct such a pick-up, the output of which can be fed into two appropriate amplifiers, one tuned for the low frequency impulse record, and the other for the higher frequency phonocardiogram.

It seems preferable that a pneumatic coupling be avoided if possible for the reasons discussed previously. The air-circuit devices have provided much useful information since their initial development more than 25 years ago, and with proper service continue to have wide applicability. But a single sensor with direct mechanical coupling from skin to transducer has both theoretical and aesthetic appeal. Such devices are now being tested and their production is awaited with interest.

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REFERENCES


ADDENDUM I

Dr. Arthur Miller has written for us the following historical sketch concerning the development of the Sanborn 374 crystal microphone:

"Early in 1939 I was approached by either Doctor Paul Dudley White or Doctor W. Trevor Cooke about the possibility of recording pulse waves simultaneously with the electrocardiograph using the two-string galvanometer system which was then the heart of the electrocardiograph apparatus in the cardiac laboratory of the Massachusetts General Hospital.

"I realized that the pressure pulsations to be recorded, in terms of the air pressure which would reach a pick-up device such as a microphone, would be relatively enormous in comparison to the sound waves which constituted the usual input to the microphone. Since the output of a simple crystal microphone in response to sound waves is measured in millivolts, this would imply that the signal generated by the pulse waves would be measured in hundreds of millivolts.

"We had been building vacuum tube amplifier type electrocardiographs since 1935 and so we were

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