'Pixie' cardiography

Accelerometer applications to phonocardiography and displacement cardiography in childhood

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The technique of deriving phonocardiograms from the 'pixie' accelerometer record by appropriate filters is described and typical examples are shown. Velocity and displacement traces have also been obtained by successive integrations of the praecordial acceleration trace, which compare closely with those recorded by conventional photoelectric methods.

An accelerometer is a small transducer which senses the acceleration of any object to which it is attached. It usually consists of a small bob weight supported on a cantilever spring (Fig. 1): upward acceleration of the base causes a downward movement of the bob relative to the base, of a magnitude dependent on the mass of the bob, the stiffness of the spring, and proportional to the acceleration applied to the base. The resonant frequency of the spring bob combination is a function of the mass of the bob and the stiffness of the spring. If a high resonant frequency is required, the spring stiffness must be high in relation to the mass, and the deflection is correspondingly small. When adjusted to give a resonant frequency of 1 kc/sec, the spring mass combination is such that the movement of the bob weight for an acceleration of 1 g (981 cm/sec^2) is about $0.2 \text{ } \mu\text{m}$.

FIG. 1 Basic components of 'pixie' accelerometer.

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Methods

Two different methods of detecting the movement and converting it to an electrical output have been used.

(a) *A semi-conductor strain gauge* The type used is designed specifically for use as a cantilever member, and is consequently very easily incorporated in an accelerometer. It is supplied by Endevco Ltd., under the trade name 'Pixie'. This transducer gives an output of 40 mV/g with 10V across the strain gauge.

(b) *An optical system* using a subminiature lamp and photo-transistor (Mullard BPX25). This gives an output of about 1V/g.

Both transducers have a resonant frequency of approximately 1 Kc/sec, but the advantage of the optical system is not nearly as great as might appear at first sight, as the phototransistor is inherently far more noisy than the strain gauge. All the clinical work reported here has in fact been carried out with the strain gauge type, and the optical transducer has been used only for experimental comparison in the laboratory (see below). Both types of transducer show negligible hysteresis and non-linearity within the working range.

When sound is transmitted through a solid or quasisolid medium, vibration will be detected at the surface of the solid, along an axis normal to the surface. The movements of the chest wall due to the events of the cardiac cycle will therefore contain lower frequency components corresponding to the gross mechanical events, and also higher frequency components due to any events that generate sound, such as turbulent flow.

The amplitude of the vibrations due to events generating sound will obviously be very small, but for a given amplitude of sinusoidal vibration the acceleration is proportional to the square of the frequency, so that vibrations in the audible

frequency range which cannot be detected by a displacement measuring device may be detected by an accelerometer. These vibrations are detected indirectly by the conventional type of phonocardiograph microphone, by conversion into changes of air pressure in the closed cavity formed when the microphone is applied to the chest wall; these changes of pressure in turn produce mechanical movements of the diaphragm of the microphone, which in turn produce an electrical signal.

When an accelerometer is applied to the chest wall, the vibrations at that particular spot are converted directly and quantitatively into an electrical signal, the praecordial acceleration trace.

The accelerometers mentioned above respond to all frequencies from zero upwards, and can therefore be used in conjunction with appropriate filters to display low-frequency accelerograms or heart sounds at choice. It is also possible to integrate the accelerometer output electrically with respect to time to produce a velocity record, and to integrate a second time to derive a displacement record. Absolute recording of velocity or displacement, which are relative quantities, can only be obtained by using some form of fixed reference point or framework; this is not necessary for recording acceleration. There is of course an arbitrary constant of integration introduced at each stage in deriving velocity and displacement: these are simply assumed to be zero, i.e. the subject as a whole is assumed to be stationary and so himself provides the frame of reference.

Velocity records are easily obtained in this way, and appear to be easier to interpret intuitively in terms of cardiac events than accelerograms. Displacement records still present considerable

FIG. 2 Accelerometer attached to chest wall of an infant.

technical difficulties except on well-trained co-operative subjects, due to the large magnitude of the respiratory movements compared with the cardiac displacements. There is not enough difference in frequency to separate the two by electrical filters without introducing gross distortion of the cardiac displacement record.

In an attempt to assess cardiac defects without recourse to catheterization, a number of workers

FIG. 3 Characteristics of the band-pass filters used to produce phonocardiograms from 'raw' acceleration signal.

FIG. 4 'Pixie' phonocardiogram of infant with secundum atrial septal defect (using filters A + D).

have examined the possibilities of obtaining the necessary information from measurements of displacement or from the low-frequency components of the phonocardiogram.

Eddleman, Hughes, and Thomas (1959) and Eddleman and Thomas (1959) have used the displacement cardiograph to differentiate between right ventricular pressure and volume loads. A volume load gives rise to an early systolic peak which is prolonged into the last third of systole with a pressure load. Similar applications have been used by Mounsey (1967), Gillam, Deliyannis, and Mounsey (1964), Deliyannis *et al.* (1964), and Benchimol, Wuh, and Dimond (1966); the subject has been reviewed in detail by Luisada (1962).

The accelerometer appeared to have important advantages, particularly in children and infants. Many conventional displacement transducers are large and heavy; they cover an appreciable area of the infant praecordium. This could seriously distort the signal recorded and also make it

FIG. 5 'Pixie' phonocardiogram of 3-month infant with ventricular septal defect showing separation of diastolic murmur (DM) from 2nd sound (see text). SM = pansystolic murmur.

difficult to record simultaneously from two or more areas of the praecordium. The small size of the accelerometer transducer (Fig. 2) thus becomes of increasing value in infants. Furthermore, one has the ability to derive both displacement and sound recordings from the same small transducer simultaneously.

A further advantage is that this does measure absolute displacement not, as many techniques do, movement relative to the chest wall or microphone mounting.

The first stage of the development work was to obtain, by appropriate filtering of the accelerometer output, a trace which was directly comparable with the trace produced by a conventional phonocardiograph. Phonocardiograms of good quality were produced by introducing a series of band-pass filters (Fig. 3) which almost completely remove low-frequency components of the praecordial acceleration trace signal; by adjusting these filters we were able to produce a series of phonocardiograms as illustrated below. The accelerometer is easily stuck to the chest wall by means of a small piece of adhesive tape. In neonates, electrocardiogram contacts were made by means of silver discs 0.5 cm in diameter applied to the shoulders and the right costal margin. These were found by trial and error to be the sites where they were least likely to be moved by the patient.

Results

Typical 'pixie' phonocardiograms recorded in an open ward are shown in the Figures.

Fig. 4 is a record from the pulmonary area of a baby with an ostium secundum atrial septal defect. There is a grade 2/6 ejection systolic murmur and fixed splitting of the second sound in the same site.

Fig. 5 is a recording from a 3-month-old infant with a ventricular septal defect. The pansystolic murmur is well shown and the diastolic murmur in this child proved of some diagnostic importance as it was suspected that the child might have a prolapsed aortic cusp giving rise to the murmur of aortic incompetence. After seeing the record it was apparent that the murmur began some time after the second heart sound and thus saved the child from an unnecessary aortogram.

Fig. 6 shows a continuous (Gibson) murmur in a 1-year-old child with a persistent ductus arteriosus.

Fig. 7 shows a recording made from a 4-year-old boy who had a severe tetrad of Fallot and his pulmonary valve was replaced with a homograft aortic valve. A few days after operation the valve developed a slight leak and a grade 1 to 2/6 early diastolic murmur was heard at the lower right sternal border. An ejection systolic murmur grade 2/6

through the graft aortic valve can also be seen in this record.

Fig. 8 shows a recording from a 3-week-old child with a hypoplastic left heart syndrome, confirmed at thoracotomy at St. George's Hospital, London. He was later transferred to the care of the Radcliffe Infirmary at Oxford. Our accelerometer derived trace (Fig. 8) is shown above the conventional phonocardiogram. (Courtesy of Dr. Aubrey Leatham at St. George's Hospital, London.)

Displacement records We hope to develop methods to overcome the difficulty in separating cardiac from respiratory chest wall displacement records.

Discussion

The first stage of development of this technique, using an accelerometer to record phonocardiograms in infancy and early childhood, is now reliable and well established, as shown in the figures above.

The accelerometer is a satisfactory alternative to the usual microphone for all phonocardiographic work, and for use on infants it is much to be preferred, because of its small size and ease of fixation.

The accelerometer also quantitatively records the low frequency components of the heart beat, but this is only a potential rather than an actual advantage at present, since the information contained in such records cannot yet be properly interpreted.

Records of displacement rather than acceleration are much easier to comprehend, and we believe that it is essential to solve the problems involved in the double integration of the accelerometer signals to give displacement recordings; but the presence of respiratory and other body movements, especially when recording from children, adds to the difficulties. That the method does hold promise enough to justify further development is, we feel, shown by Fig. 9 which shows simultaneous displacement records obtained directly (using a fixed reference and an optical system) and by double integration of the acceleration tracing. Fig. 10 shows the praecordial acceleration trace recorded with

FIG. 6 Phonocardiogram showing a persistent ductus continuous Gibson murmur (GM) in a 1-year-old child.

FIG. 7 Phonocardiogram of 4-year-old with postoperative pulmonary incompetence (EDM) after total correction of tetrad of Fallot. ESM = ejection systolic murmur.

FIG. 8a 'Pixie' phonocardiogram of neonate with hypoplasia of ascending aorta. ESM = ejection systolic murmur.

FIG. 8b Conventional phonocardiogram of infant shown in Fig. 8a. RESPIRATION = inspiration upwards.

FIG. 9 Simultaneous optical (D_1) and accelerometer derived (D_2) displacement records. Outward displacement downwards. A = PACT trace. (UV recording retouched for reproduction.)

the 'pixie' accelerometer and below a trace derived by double differentiation of the photoelectric record. These records were taken on a co-operative adult subject, and neither method of recording displacement would be workable

on a baby; we expect however to be able to obtain displacement records on any patient after further technical improvements have been made.

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FIG. 10 Simultaneous praecordial acceleration trace recorded directly (A_1) and also obtained by double differentiation of photoelectric displacement record. (A_2) outward displacement (D) downwards. This shows that it is possible to derive acceleration from a displacement transducer by differentiation in the same way that the accelerometer record can be processed to produce displacement (by double integration).

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