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Transcutaneous aortovelography
A quantitative evaluation

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The haemotachograph is a non-invasive ultrasonic Doppler-shift instrument designed to measure the velocity of blood in the arch of the aorta by a technique referred to as transcutaneous aortovelography. Its accuracy has been assessed at cardiac catheterization in 20 patients. When transcutaneous aortovelographic values were compared with stroke volume determined by standard invasive techniques, a good proportional agreement was found. The accuracy of absolute flow values, as calculated from transcutaneous aortovelography and dimensional data, was, however, poor. Peak velocity determined from transcutaneous aortovelographic tracings agreed well with values obtained with a catheter tip electromagnetic velocity probe. Transcutaneous aortovelography is a useful non-invasive technique which can be used to determine phasic blood flow velocity in the aortic arch and to follow changes in cardiac output over a period of time.

Most available methods for measuring cardiac output and the haemodynamic indices which are thought to provide a measurement of cardiac functional status require that catheters or flow probes be inserted into arteries and accurate measurements made under static and strictly controlled conditions (Cliffe, 1973; Mills, 1972). Established non-invasive methods for measuring cardiac output (Pugh 1972; Bosman *et al.*, 1964; Karatzas *et al.*, 1967) depend on a constant ventilation—perfusion ratio in the lungs and thus have obvious limitations when used under clinical conditions. Ultrasonic methods for estimating ventricular volumes have proved useful in valvular disease (Feigenbaum *et al.*, 1969; Feigenbaum, 1974) but difficulties arise when ventricular dysnergy is present (Heikkilä *et al.*, 1972; Gibson and Brown, 1974). The development of a Doppler-shift ultrasound instrument by Light and his co-workers (Light and Cross, 1972; Light, 1974; Light *et al.*, 1974; Cross and Light, 1974) provides a non-invasive measurement of blood velocity in the arch of the aorta and promises to be a useful advance in non-invasive technology. We have assessed the performance of this instrument in measuring stroke output and peak velocity, by comparing it with standard invasive techniques.

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Materials and methods

The instrument (Fig. 1) consists of a direction-resolving Doppler unit which allows the separate analysis of coexisting signals from advancing and receding flow, a Doppler probe containing both transmitting and receiving transducers, and an on-line spectral analyser. It is compact and mobile and can conveniently be moved to the bedside. Unlike much of the conventional Doppler instrumentation, it retains the linearity and lack of need for calibration which are intrinsic to the Doppler phenomenon. Transcutaneous aortovelography is the name that has been given to this technique for sensing

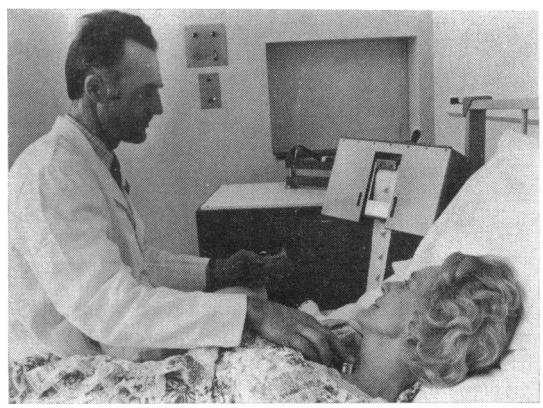

FIG. 1 *The non-invasive haemotachograph in use.*

blood velocity and the instrument has been named the non-invasive haemotachograph.

Basic theory of transcutaneous aortovelography

If a vibration of a known frequency, F, is backscattered by a target moving with a velocity V at an angle θ to the direction of incidence of the vibration, the backscattered energy will have a frequency $F \pm \Delta F$, where ΔF, the Doppler shift, is given by $\Delta F = \frac{2F}{C} V \cdot \text{Cos } \theta$. As c, the propagation velocity of the vibration in tissue, is known to within 1 per cent and F has a value which is precisely known for a particular instrument, V cos θ can be accurately calculated from the Doppler shift ΔF, without need for calibration.

To obtain the velocity V of the moving target, the angle θ must be known, except for the special case when it is close to zero. In that case, provided θ is less than 25°, cos θ can be taken to equal 0·95 with a maximum error of ±5 per cent, thus allowing the actual velocity V to be calculated within that margin of error. The sign of the Doppler shift indicates whether flow is towards (+) or away (−) from the probe containing the transducers.

In order that signals from tissue vibrations do not interfere with the analysis of the wanted signals from blood flow, low Doppler shifts (corresponding to in-line velocities of less than 10 cm/s) are suppressed. Thus very low velocities, as occur during diastole, cannot be seen, but the measurement of higher velocities is not affected.

Technique for using haemotachograph

The arch of the aorta is a suitable vessel for transcutaneous aortovelography because its anatomical position allows the ultrasonic beam to be closely aligned with the direction of flow (Fig. 2) and the angle θ is likely to be less than 25° (Light, 1974). Furthermore, this part of the aorta carries most of the cardiac output and so the results are not unduly affected by regulatory mechanisms confined to any one kind of vascular bed, and it is close enough to the heart to reflect changes in left ventricular function.

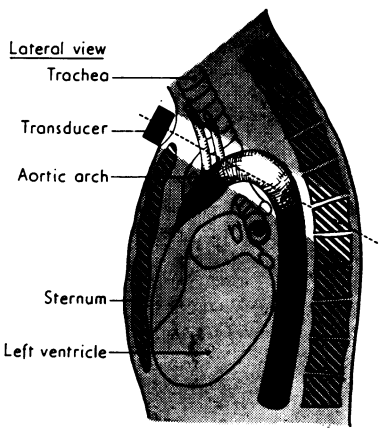

FIG. 2 *Probable path of ultrasonic beam. The sagittal section illustrates the in-line incidence of the ultrasonic beam to the arch of the aorta. The highest Doppler shifts come from the part of the vessel shown in white.*

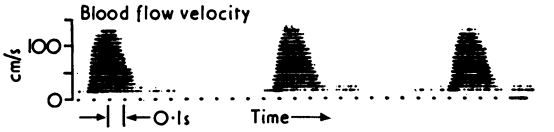

FIG. 3 *On-line transcutaneous aortic velocity recordings. The outline of the darkened areas is the velocity waveform, and the area under the systolic velocity curve should be proportional to stroke volume.*

To obtain the signal, the Doppler probe is applied to the suprasternal notch and pointed towards the aortic arch. Using the sounds produced by the processed Doppler-shift frequencies and the recording as a guide, the probe is manoeuvred so that systolic flow complexes of clear outline are obtained (Fig. 3). As viewed from the transducer, systolic blood flow in the arch of the aorta is receding and thus gives negative Doppler shifts. To ensure selective analysis of aortic flow, only negative Doppler shifts are analysed and displayed. The *highest* Doppler shift at any one time, which appears as the *outline* of the waveform, measures the highest instantaneous blood velocity within the vessel. Lesser frequency shifts are also returned from regions near the vessel wall and those parts of the vessel carrying flow at a substantial angle to the beam, but since attention is paid only to the outline of the waveform these are automatically discounted. Because of its inclination to the beam, pulmonary artery flow also will normally return only lesser shifts of frequency, and, therefore, not interfere with the measurement.

Relation between measured variable and flow

The variable indicated by transcutaneous aortovelography is thus the highest flow velocity existing in the insonated part of the transverse aorta at any one time. This is a good index of the flow velocity averaged over the whole cross-sectional area of the vessel, providing the transverse flow profile in the particular subject remains substantially constant (a) throughout systole and (b) between serial measurements. Several studies (e.g. Schultz *et al.*, 1969) have shown that flow profiles do not change greatly throughout systole. Moreover, on fluid dynamic grounds, the profile should normally remain constant in any one subject over lengthy periods of time. (Changes to the flow profile are, however, to be expected if the aortic tract is deformed, e.g. by a tumour progressively compressing the aorta around or proximal to the measurement region. Under such circumstances, blood velocity measurements by transcutaneous aortovelography will be directly comparable as an index of flow only over relatively short periods.)

When, as is normally the case, the transverse flow profile is relatively flat, the velocity measured by transcutaneous aortovelography will approximate to the average velocity throughout the vessel. However, serial transcutaneous aortovelographic measurements in any one subject are meaningful indices of blood velocity *whatever* the flow profile happens to be, provided only that the profile remains constant in that subject.

For velocity to be an accurate index of flow, it is further necessary that the cross-sectional area of the vessel remains constant between measurements. This is unlikely to be exactly true for an elastic vessel like the aorta, but non-invasive observations suggest that under most circumstances the magnitude of the changes is not such as to introduce major errors.

For a fuller treatment of the theoretical bases, see Light (1974) and Cross and Light (1974).

One might, therefore, expect that, with relatively rare and largely predictable exceptions, transcutaneous aortovelography will give readings which are approximately proportional to those produced by other velocity of flow indicating methods. Identity of readings with other velocity-sensing techniques would, however, be expected only if these measured the same variable as transcutaneous aortovelography, namely the highest flow velocity in the insonated region of the aorta.

The studies reported here were intended to test these expectations.

Analysis of transcutaneous aortovelographic signals

A drawing indicating how the various measurements are extracted from the waveform is shown in Fig. 4. The outline of the area is the velocity waveform and the area under the systolic velocity curve should be proportional to stroke volume (see Appendix). In order to calculate this area and hence the mean velocity, the waveform was treated as triangular (Cross and Light, 1974). Mean velocity, $\bar{v}$, is obtained by dividing the area by the duration of the cardiac cycle. Peak velocity is easily measured and the slope of the tangent to the early part of the waveform represents acceleration in early systole. The duration of the flow and of the acceleration phase can also be measured. Pre-ejection periods can be derived if an electrocardiographic signal is simultaneously recorded on the transcutaneous aortovelographic tracing.

The use of a triangular approximation to the actual waveform overestimates the area by some 10 to 25 per cent, but the error introduced is normally constant in any one subject. As the prime objective in these studies was to establish the degree of proportionality in any one patient between measures of flow obtained by transcutaneous aortovelography and by established techniques, this approximation introduced little error. Agreement with absolute values will however be affected.

Experimental procedure

The accuracy of this instrument was tested in 20 patients (15 men and 5 women), between the ages of 39 and 65 years, undergoing routine diagnostic cardiac catheterization for the investigation of ischaemic heart

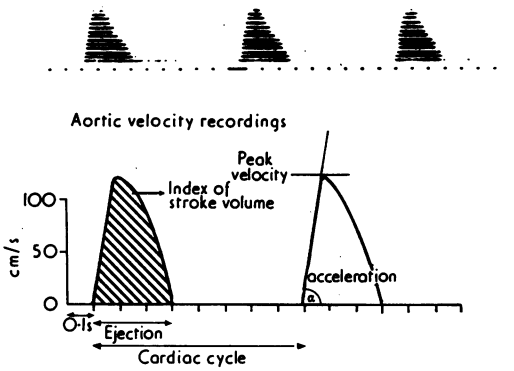

FIG. 4 *Drawings of the signals obtained by transcutaneous aortovelography indicate how the various measurements are extracted from the waveform. For the purpose of calculating the area under the curve, the waveform is treated as triangular. Mean velocity is obtained by dividing this area by the duration of the cardiac cycle. Acceleration is given by tan α.*

disease. Cardiac output was measured by an indicator dilution technique at rest and during atrial pacing at rates up to 160/min. A bolus of 10 mg indocyanine green was injected into the pulmonary artery and arterial blood was withdrawn from the femoral artery by a constant rate syringe through a cuvette densitometer[1] feeding a chart recorder. All cardiac output measurements were made in duplicate and stroke output was obtained by dividing the result by the heart rate during inscription of the curve. Transcutaneous aortovelographic observations of aortic velocity were made just after the indocyanine green injections at each heart rate. The stroke output was calculated from the product of the area under the velocity curve using the triangular approximation (the average of some 10 beats immediately after the injection was taken) and the cross-sectional area of the transverse aorta. The last was obtained from a lateral aortic root angiogram obtained at the end of the procedure. The diameter of the distal part of the aortic arch was measured from systolic films and corrected for magnification. Assuming a perfectly flat velocity profile in the arch of the aorta, this product should give volume flow into the descending aorta and therefore some 75 per cent of cardiac output, since the flow to the coronary arteries, head, neck, and upper limbs calculated from physiological data (Keele and Neil, 1971) accounts for approximately 25 per cent of the cardiac output.

In 7 of these patients, after determination of cardiac output, an electromagnetic catheter tip velocity probe (Mills and Shillingford 1967) was introduced via the right femoral artery. The tip was positioned in the distal bend of the transverse aorta, the site of the transcutaneous aortovelographic observations, in the hope of obtaining the most closely comparable measure-

[1]Gilford Instruments Ltd.

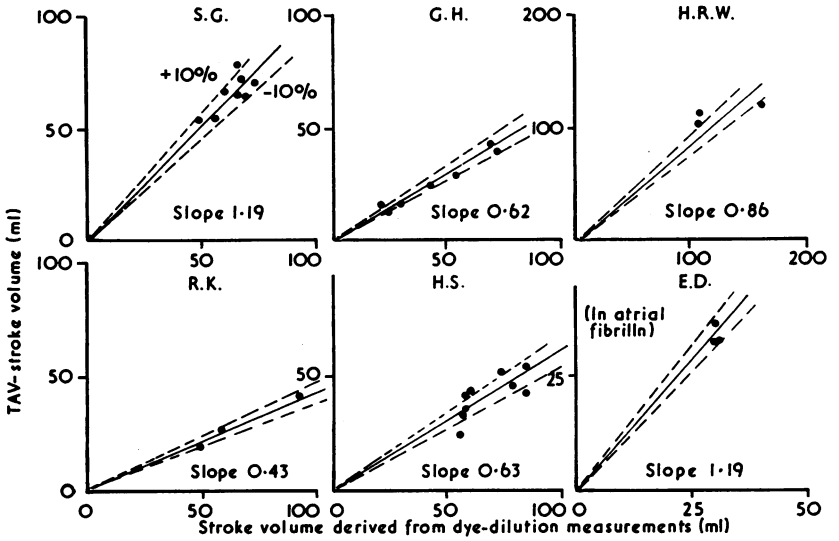

FIG. 5 *Correlations between stroke volumes in 6 patients, selected to show extremes of the spread found, as calculated from dye dilution measurements (plotted horizontally) and from transcutaneous aortovelographic readings together with angiographic measurements of an aortic diameter (plotted vertically). Pacing was used to vary the stroke volume. As no correction was made for the loss of flow to head, arms, and the coronary circulation, a slope of approximately 0·75 would be expected for the line of best fit (see text). Dashed lines indicate plus/minus 10 per cent variation from proportionality.*

ments. This, however, made it difficult to manoeuvre the catheter so that its tip was clear of the wall—in several subjects velocity readings differing by a factor of 4 to 1 could be obtained by manoeuvring the catheter tip.

The procedure adopted in the present studies was to place the tip so as to yield the highest stable readings which could be obtained without delaying the investigation. The peak velocities of individual beats were compared, except when nearly identical beats resulted from pacing at a fixed rate. Averages of 10 successive peaks were then compared. The level of the E-M trace in mid and late diastole was taken as zero (Gabe *et al.*, 1969).

Results

Stroke output

The result of these studies in 6 patients *selected to show the extremes that were encountered* is shown in Fig. 5. All show approximate proportionality, but major discrepancies in absolute values appear in several of the subjects as shown by the deviation of the observed slope of the 'best fit' line (visually drawn to pass through the origin) from the expected value of 0·75. The correlation points obtained in all subjects have been combined in Fig. 6 in such a way that the degree of proportionality found is clearly apparent. This has been achieved by adjusting the vertical scale of the individual studies so as to make all slopes equal to unity and then superimposing the results. The coefficient of variation (standard

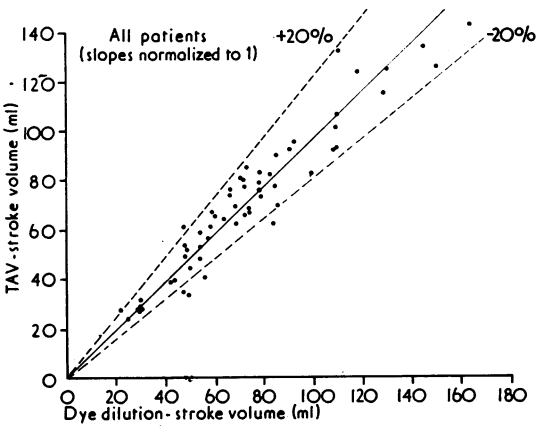

FIG. 6 *Pooled results from the patients in the series normalized so as to show the degree of proportionality in any one patient between transcutaneous aortovelography and dye dilution measures of stroke volume. Dashed lines indicate plus/minus 20 per cent deviation from exact proportionality.*

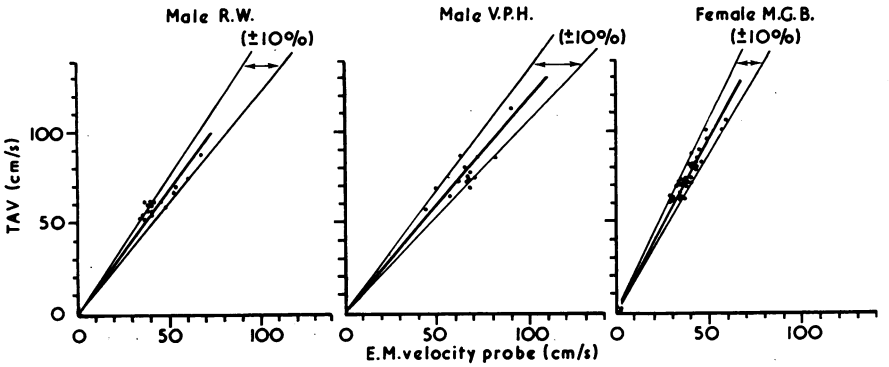

FIG. 7 *Correlation of peak velocity in 3 patients which illustrate the range of results found. Values obtained by transcutaneous aortovelography are plotted on the vertical axis while those obtained by an electromagnetic catheter tip velocity probe placed in the arch of the aorta are plotted horizontally. Plots (a) and (b) show results on two patients whose heart rate was varied by pacing. Patient (c) was in atrial fibrillation. The outer lines indicate plus/minus 10 per cent deviation from proportionality.*

deviation/mean), which is a measure of the departure of the observations from strict proportionality between the two techniques, was found to be 13 per cent.

Peak velocity

The results obtained in three studies, which illustrate the full spread in absolute values, is shown in Fig. 7. Good proportionality was found between the two techniques in all subjects. When the correlation points in the 7 patients (which included 2 in atrial fibrillation) were combined as above, the coefficient of variation was found to be 6 per cent.

Discussion

This technique is safe (power level less than 100 mW/cm^2) and convenient. Adequate signals can be obtained in 90 per cent of subjects. Because of its non-invasive nature, the investigation can be repeated as often as the state of the patient demands.

Proportionality with flow rate

The results of our experiments are encouraging and support the theoretical expectation that under most conditions there is good proportionality between the transcutaneous velocity readings obtained by this technique and the true flow rate. This suggests that transcutaneous aortovelography is capable of relative measurements (the quantification of changes) of velocity and flow in individual subjects. On average, there also was fair agreement on absolute values, but the error approached 2:1 in some subjects.

The poor agreement on absolute values sometimes found is not surprising, since good agreement would only be expected if the velocity profile in the aortic arch were exactly flat. Errors in the evaluation of the transcutaneous aortovelographic records (triangular approximation), in the estimation of the cross-sectional area of the transverse aorta (radiographic magnification and assumption of circular cross-section), and in the approximation that 25 per cent of the cardiac output is distributed to the coronary arteries, head, neck, and upper limbs could contribute to the poor agreement of absolute values. We suspect, however, that departures from flatness of the flow profile and from circularity of cross-section are mainly responsible.

The observed proportionality between the mean transcutaneous aortovelographic velocity and cardiac output obtained by green dye suggests that in a given subject these factors remain relatively constant. While this will commonly be so, circumstances can be foreseen where they may vary substantially. Thus, compression of the aortic arch by a tumour might progressively change the velocity profile, while influences that selectively affect the cerebral circulation will modify the proportion of cardiac output entering the descending aorta (see Appendix). In other circumstances changes in systolic blood pressure may affect the cross-sectional area of the aorta, but data obtained by non-invasive techniques suggest that gross changes in pressure are required to give clinically significant changes in adults (Goldberg, 1971; Olson and Shelton, 1972).

In patients with aortic regurgitation, the systolic

waveform normally displayed represents gross ejected stroke volume. It may prove possible to estimate the fraction of regurgitant flow by observing also the reverse flow velocities in the aorta, which can be seen on an alternative centre-zero display range (Light, 1974).

Velocity comparisons

The observed agreement between the velocity measurement obtained by transcutaneous aortovelography and the electromagnetic catheter tip velocity probe is satisfactory when the difference between the nature of the two measurements is borne in mind.

The electromagnetic velocity probe is an accurate method of measuring the velocity in the immediate vicinity of the catheter, provided this is roughly aligned (within $<45°$) with the direction of flow. Transcutaneous aortovelography, on the other hand, registers the highest velocity in the insonated portion of the arch. Agreement between the actual values recorded by the two techniques would, therefore, be expected only if the catheter tip were in the part of the cross-section carrying the highest velocity flow and fairly well aligned to its direction; otherwise the electromagnetic system should, as was indeed observed, give lower readings which, however, are proportional to those of transcutaneous aortovelography.

Flow profile

These studies also produced some evidence suggesting that the transverse flow profile in the aorta is remarkably little affected by irregularities in intracardiac haemodynamics. Thus, the departures from exact proportionality in a patient with atrial fibrillation (Fig. 7c) were no greater than those seen in the paced patients. Likewise the points representing the occasional ventricular extrasystoles in the paced patients (which are included in the plots of Fig. 7a and b) did not deviate in an obvious way from the pattern produced by regular beats. Whether this is consistently true of the whole range of aberrant or diskinetic ventricular contractions requires further study.

Specificity of measurement The above results by themselves do not prove that the transcutaneous aortovelographic measurement, i.e. the *outline* of the recorded signal, arises from aortic flow. Negative Doppler shifts will also be returned by the pulmonary artery or veins, which may well be within the beam. By virtue of the inclination to the ultrasonic beam, however, it is improbable that signals originating from the *pulmonary artery* would contain Doppler shifts high enough to contribute to the outline of the spectrum unless it was carrying flow of disproportionately high velocity.[1] Evidence which precludes interference to the outline from this source has been more fully reported elsewhere (Light, 1974):

1) The negligible effect of quite substantial variation of the direction of the transducer and hence of the ultrasonic beam on the signal outline indicates that the direction of flow is nearly in line with the beam.
2) The finding that in a patient with subvalvular stenosis the incidence of waveform abnormalities was identical in the transcutaneous aortovelographic recording and in that obtained from a catheter tip velocity probe in the ascending aorta.
3) In slow and deep respiration, the phase of the respiratory modulation observed was that appropriate to aortic blood flow but not that to pulmonary artery flow. Responses to Valsalva manoeuvres were similarly characteristic of aortic flow.
4) Further confirmation is afforded by observations in a proven case of atrial septal defect with a 4:1 shunt where, having obtained an aortic velocity waveform from the usual position, lowering the aim of the ultrasonic beam produced a different waveform from exceptionally fast pulmonary artery flow.

Such observations do not rule out the possibility that signals from the pulmonary artery can obscure the aortic velocity outline in an occasional subject and some vigilance is, therefore, still required.

Venous signals are commonly seen on transcutaneous aortovelographic tracings but normally give very low Doppler shifts which are easily distinguished from aortic signals. However, in certain conditions venous flow may be very pulsatile with resultant high peak velocities which could mimic aortic flow. Such venous waveforms are, however, characterized by substantial respiratory modulation and are readily differentiated from the coexisting aortic signal by their post-systolic timing. The transcutaneous aortovelographic display, in which signals from different vessels often register in different shades of grey, further helps in distinguishing such interference (Cross and Light, 1974).

[1]With the signal handling and presentation methods (spectral analysis and display) used in the non-invasive haemotachograph, the presence of even very powerful signals with relatively low Doppler shifts does not impair recognition of the wanted variable, which is the highest Doppler shift simultaneously present. The spectral presentation also often allows intersecting flow waveforms, as from venous flow, to be resolved. This is in contrast to single-line representations of the signal, particularly if these indicate an average of all the negative Doppler shifts present.

Other information obtainable

In addition to indices of flow, other variables of haemodynamic interest can be obtained from velocity measurements. The clinical value of observing peak velocity or the duration of the flow phase (Perloff and Reichek, 1972) or acceleration (Bennett *et al.*, 1974; Noble, Trenchard, and Guz, 1966) which can all be derived from the waveform obtained by transcutaneous aortovelography is as yet uncertain, though these measurements have recently aroused much interest (Mitchell and Wildenthal, 1972; Bos, 1972; Noble, 1972). These measurements or changes in them as a result of deliberate controlled stressing as by atrial pacing (Sowton *et al.*, 1967; Linhart, 1971) may give some indication of left ventricular function. In contrast to echocardiographic observations of segmental ventricular wall motion, which characterize local abnormalities (Gibson and Brown, 1974), transcutaneous aortovelography should give complementary information on overall left ventricular function.

Some factors relevant to the interpretation of blood velocity data are discussed by Light (1976), and the early results of a clinical evaluation are described by Buchtal, Hanson, and Peisach (1976).

Conclusion

We conclude that transcutaneous aortovelography is a useful non-invasive technique for following serial changes in stroke output and other indices of left ventricular function. The ability to assess, as often as desired, the response of a patient to a variety of therapeutic interventions should prove valuable in intensive care and coronary units. Transcutaneous aortovelographic measurements should similarly facilitate human studies into the inotropic and haemodynamic effect of drugs or anaesthetic agents which affect the circulation and in particular the time course of their action. The application of the technique for the measurement of absolute flow is ruled out until convenient non-invasive methods can be developed to measure the other factors discussed above which affect volume flow. The technique is capable of further refinement, and experience with it is still limited. Further use should allow us to define more clearly its scope of application in patient care and diagnosis.

APPENDIX

Relation between velocity, as observed by transcutaneous aortovelography, and measures of blood flow

If the transverse flow profile is exactly flat, the *area* (L) of the systolic complex (the darkened area) represents the length of the column taken up by the volume of blood which passes the measurement region in the corresponding heart beat.

The product of this area and the cross-sectional area of the transverse aorta (A) should give the part of the stroke volume entering the descending aorta. The full stroke volume (SV) will be given by

$$SV = L.A.f. \quad \ldots\ldots(1)$$

where f=the ratio between flows in the ascending and descending aorta. Similarly, the above product, multiplied by heart rate (n), should give the cardiac output (CO)—

$$CO = n.L.A.f. \quad \ldots\ldots(2)$$

Another—equivalent—expression for cardiac output is—

$$CO = \bar{v}.A.f. \quad \ldots\ldots(3)$$

where $\bar{v}$ is the time-average of the indicated blood velocity.

When, as will be the case in practice, the transverse flow profile is not perfectly flat, another factor, p, must be introduced:—

$$p = \frac{\text{Average velocity throughout lumen}}{\text{Highest velocity in insonated region}}.$$

Equations (1) to (3) now become

$$SV = L.A.f.p. \quad (1)$$
$$CO = n.L.A.f.p. \quad (2)$$
$$CO = \bar{v}.A.f.p. \quad (3)$$

Exact proportionality in serial observations between velocities observed by transcutaneous aortovelography and flow rate into the descending aorta thus depend on two factors remaining constant in any one patient: the profile factor, p, and the cross-sectional area of the aorta, A.

As argued in the text, these two factors will be constant to a first approximation over a considerable range of conditions. This is also borne out by the results of the present study, in which stroke volumes (but not necessarily cardiac output) varied greatly.

Largely because of the autoregulation of the cerebral and coronary circulations, the factor, f, will fall with cardiac output when this is pathologically low. As a result, though transcutaneous aortovelography continues to present flow into the descending aorta with the accuracy to which p and A are constant, the sensitivity of the measurement to changes in cardiac output *increases* at low levels of the latter. Changes in cardiac output are thus more clearly apparent, though the accuracy with which they may be measured is decreased.

At pathologically low levels of cardiac output it is most appropriate to think of transcutaneous aortovelography as providing a measure of blood flow into the descending aorta. As this is also the flow available to perfuse the abdominal organs and the majority of the skeletal tissues, the variable thus indicated is one of importance to the patient's survival.

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