L. H. LIGHT
BIOENGINEERING DIVN.
CLINICAL RESEARCH
01 864 5311 CENTRE x 2404/265
HARROW, MIDDX., U.K.
HA1 3UJ

# Aortic blood velocity measurement by transcutaneous aortovelography and its clinical applications.

by L.H. Light,
Bioengineering Divn, Clinical Research Centre,
Harrow, U.K.

Aortic blood velocity observations complement echocardiography by readily giving information on two important variables which are difficult or impossible to assess echocardiographically: the overall effect of left ventricular contraction and serial changes in left ventricular function.

A technique which maximises convenience and reproducibility in the measurement of mainstream aortic blood velocity has been described 1), 2), 3). In Transcutaneous Aortovelography (T.A.V.), a relatively wide beam of continuous ultrasound is used which is directed from the suprasternal notch towards the transverse aorta (fig. 1). A near-tangential approach to flow is obtained which virtually eliminates the effect

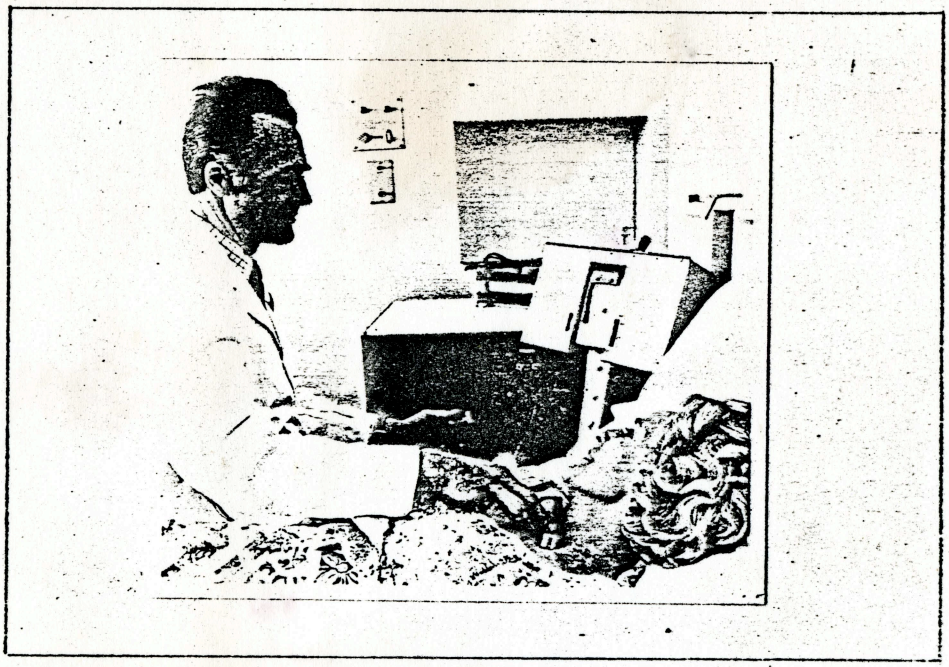

fig. 1. Measurement of aortic blood velocity by transcutaneous aortovelography. Operation of the instrument by doctor, nurse or technician is simple and quickly learnt. There is no discomfort to the patient, who is preferably supine, as this position generally allows a better signal to be obtained.

of the angle term in the Doppler equation 4) (fig. 2). Mainstream blood velocity can thus be calculated, without the need for any calibration, from the highest negative Doppler shift in the signal backscattered at any one time by the red blood corpuscles moving in the arch. The same applies to the signals from the pulmonary artery which may be obtained in children and a minority of adults by the approach "2" in fig. 2a.

Although means exist for displaying this highest Doppler shift in isolation 5), 6), 7), the full spectrum is displayed on-line for the sake of reliability: A sharp outline to the spectrum verifies that mainstream flow has indeed been insonated 8), while the occasional presence of interference from flow in the innominate vein is usually visible in a different shade of grey. Another advantage of spectral analysis is that the spectral outline is visible even for signal-to-noise ratios below unity, so that measurements can be carried out in patients giving poor return signals.

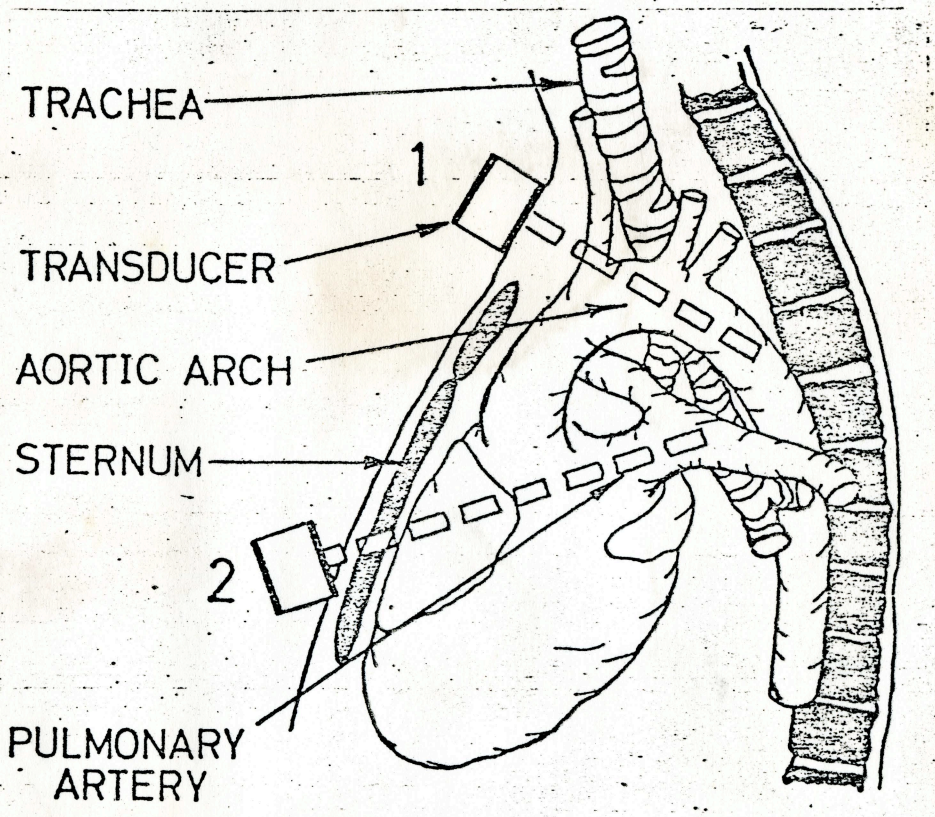


fig. 2a. Lateral view of transducer positions and ultrasonic pathways to aortic arch and pulmonary artery trunk. In each case systolic blood flow is receding and some of the flow is within 26° of the direction of the ultrasound beam, so that reproducible velocity measurements can be obtained *by calculation* from the highest instantaneous negative Doppler shift in the signal backscattered by the red blood cells.

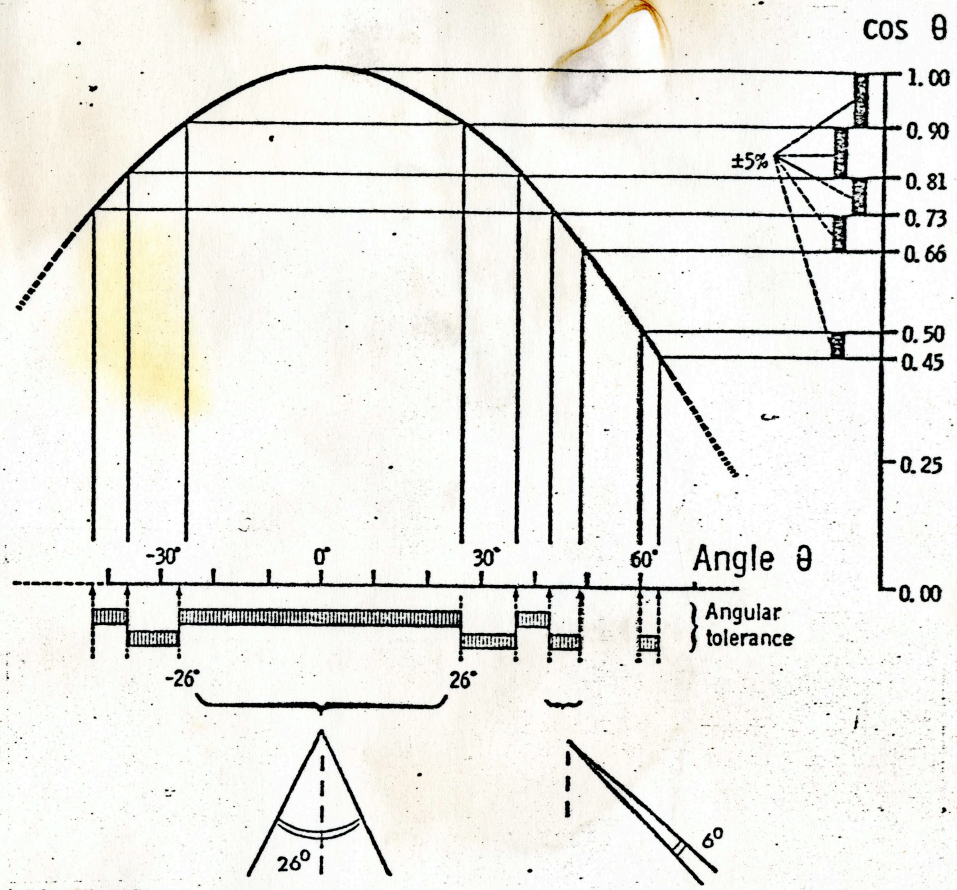


fig. 2b. For quantitative and reproducible Doppler velocity (v) measurements, the angle θ between flow and ultrasound beam must in general be accurately known and exactly reproduced in serial measurements. Exceptionally, for nearly in-line incidence, there is a wide tolerance on the angle (up to ± 26° from exactly in-line for ± 5 percent accuracy). This is a consequence of the cosine-dependence of the Doppler shifts, which are given by $\Delta f = 2.55v \cos \theta$ for a 2MHz beam. The figure indicates the angular tolerance (shaded bars, bottom) for ± 5 percent measurement reproducibility. Actual angles corresponding to this tolerance are also shown.

The direction-resolving continuous-wave system and a display highlighting the maximum negative Doppler shift, which are used in the instrument, reject most unwanted signals while avoiding the adjustment required to find the appropriate depth which would be required in a range-gated (pulsed) system. Range/velocity ambiguity problems are also avoided.

*Verification*

Comparisons during diagnostic catherisation with intravascular blood velocity measurements by electromagnetic catheter, (S.E. Labs.) showed good proportionality

Figure 3a

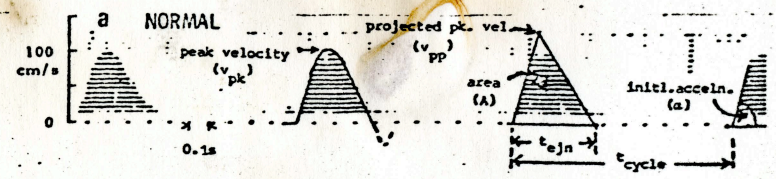


Figure 3b

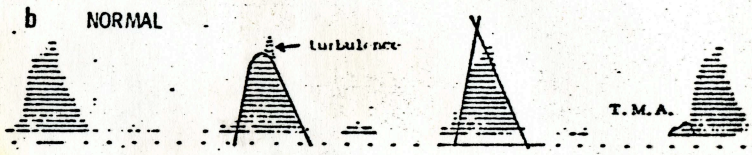


Figure 3c

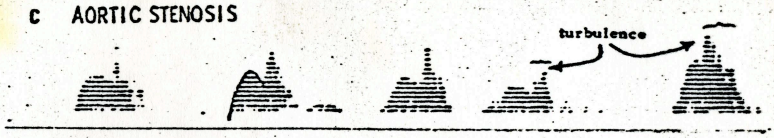


Figure 3d


Figure 3e


Figure 3f

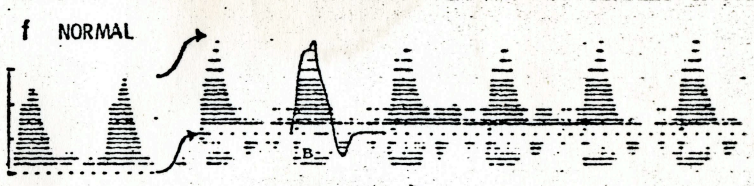


Figure 3g

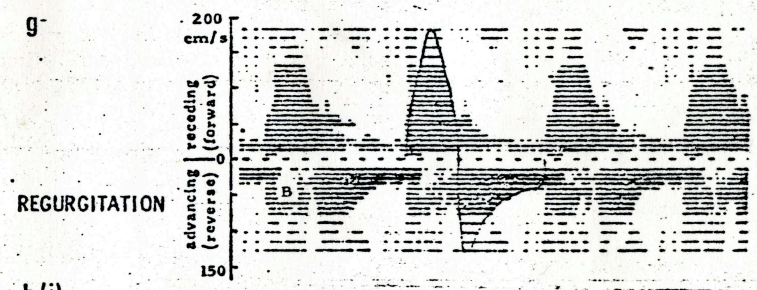


Figure 3h

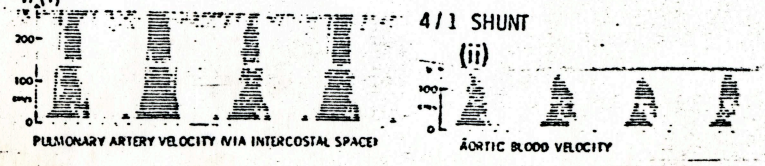

fig. 3. Aortic blood velocity measurements. Normally, only negative Doppler shifts (from blood receding from the transducer) are analysed, (a) - (e). A distinct outline to the spectrum (darkened area) indicates the time-course of mainstream flow velocity during systole. The vertical scale is common to traces (a) - (g). Derived variables of haemodynamic interest are shown, as is an approximate form of waveform analysis in which triangles are circumscribed round the systolic complexes. The area of the complex is a measure of stroke volume in any one subject.

a) Normal waveform: a smooth outline indicates laminar flow.
b) Normal waveform: a short spike, indicating minimal flow disturbance, is commonly seen just after the systolic peak in young subjects. (T.M.A. = tissue motion artefact).
c) Sustained irregularity of outline with delayed onset is found when there is an upstream obstruction to flow, as in aortic stenosis.
d) Characteristic double peaks, or a 'shoulder' on the downstroke are found in obstructed beats in hypertrophic obstructive cardiomyopathy. The R-spike from a co-recorded ECG is seen projecting downwards before each complex.
e) Haemodynamic impairment following myocardial infarction is typically signalled by reduced peak velocity and ejection time. Acceleration is not necessarily subnormal during early systole, but is poorly sustained.
f) Aortic backflow (in addition to systolic branch artery flow, "B") is seen below the raised zero line in a bi-directional display. This trace shows the normal brief post-systolic flow reversal.
g) Excess backflow indicates aortic regurgitation, the severity of which can be estimated from the ratio of the systolic and diastolic areas. (Trace (g) was assembled from separate recordings of forward and reverse flow).
h) By the use of an intercostal approach (fig. 2), blood velocity can also be measured in the pulmonary artery (i) of children. This exceeds aortic blood velocity (ii) in cases of severe left to right shunts, as in the 4:1 shunt illustrated.

9) in each of 7 subjects between peak velocities recorded by the two techniques (S.D. = 6 percent), with the degree of agreement on absolute values which might be expected in view of the difficulty of placing the catheter in mainstream flow. Proportionality was also observed between the area of TAV systolic complex and stroke volume as calculated from dye dilution studies (S.D. = 13 percent) 9). It did not, however, prove possible to calculate with adequate accuracy the absolute cardiac output when a single aortic diameter measurement was also available, one probable reason being the non-circularity of the aortic cross-section which has been observed in some individuals. These findings have been confirmed by Mackay & Hechtman 10) using essentially the same technique, and by Huntsman et al 7) using a spectral outline follower.

The negligible angle-dependence of the signal 8) around the optimum and the consistency 11) found in multi-observer reproducibility trials (S.D.= 7 percent) provide circumstantial evidence that the measurement is of actual mainstream blood velocity. Hypodynamic and hyperdynamic conditions can therefore be recognised as deviations from the normal range. Normal peak blood velocities were found to be remarkably independent of age throughout childhood 12) (135 cm/s±18 cm/s S.D.), but to fall gradually with age in the over-thirties.

*Quantitation*

Quantitation by TAV is thus in terms of blood velocity (peak and mean), expressed in cm/s. Relative blood flow - including the ratio of serial cardiac output values - can also be quantitated by virtue of the close proportionality 9), 13) which exists under most circumstances in any one subject between mean blood velocity and volume blood flow in l/min. A single simultaneous measurement of cardiac output by another technique is required to 'calibrate' the patient when absolute values of cardiac output are essential. However, abnormalities of the absolute level of cardiac output appear to be reflected in abnormalities of the mean aortic blood velocity and usually also in the waveform pattern. It is thus likely that most - if not all - of the clinically useful information on cardiac output presently obtained from invasive measurements is available in TAV recordings, with extra information on the manner of left ventricular ejection being given by the pulsatile waveform.

*Applications*

Applications fall into two categories, patient assessment, where abnormalities of scale or of wave shape give the required information, and serial monitoring in which the relationship between blood velocity and blood flow allows changes in body perfusion and left heart action to be observed. The results of several reproducibility studies suggest that changes exceeding 10 percent can be detected with greater than 90 percent confidence.

*Patient assessment*

Abnormalities of scale: abnormally high velocities are seen in thyrotoxicosis and severe anaemia, while low values are found in a variety of hypodynamic conditions, including hypovolaemia. In severe ischaemic heart disease and hypovolaemia, abnormally short flow-time ratios (ejection period divided by cycle period) are also found, (fig. 3e). Back flow in excess of the brief physiological post-systolic flow reversal indicates aortic regurgitation. Backflow is seen (in addition to systolic flow in the branch arteries and occasional venous signals) below the centre-zero line in a bi-directional display. (fig. 3f,g). Quantitation of aortic regurgitation (fig. 3g) appears to be feasible by comparing the area of the forward stroke volume with that of reverse flow velocity 14). This is in spite of the often appreciable variation in aortic cross section and flow profile which exists in this condition between systole and diastole.*

Sustained irregularities of outline, indicating turbulence, are seen in aortic stenosis and other conditions in which the left ventricular outflow tract is partially obstructed (fig. 3c). Quantitation is not possible while an irregular outline indicates that eddies are superimposed on the forward motion of the blood.

* Aortic and mitral regurgitation can also be assessed from the non-quantitative aortic velocity waveform which may be obtained from more elementary instrumentation 19), 20). This however, requires expert and relatively time-consuming handling.

In hypertrophic obstructive cardiomyopathy, a characteristic double ejection or a 'plateau' on the down-stroke are seen in obstructed beats, (fig. 3d), which may if necessary be provoked for diagnostic purposes by suitable manoeuvres 14).

Marked respiratory modulation of peak velocity and area of systolic complex may be found in constrictive pericarditis and cardiac tamponade, and is also seen in other circumstances when the circulation is embarrassed. Irregular beat to beat variations of stroke volume are evident in arrythmias, e.g. the ectopic in fig. 3c.

In severe left to right shunts, pulmonary artery velocities have been found to be higher than aortic velocities (fig. 3h). As the cross-sectional areas of the two vessels are not usually comparable in this condition, the ratio of velocities does not necessarily give the volumetric flow ratio. The extent to which such velocity comparisons are useful in the evaluation of shunts is currently being studied 14).

*Monitoring applications*

Aortic blood velocity is a more direct index of body perfusion and left ventricular function than variables like blood pressure, central venous pressure and left atrial pressure which are commonly used in intensive and coronary care. It, however, also supplements these latter measurements and makes them more readily interpretable. Trends and the patients response to therapy can be seen - the latter is particularly valuable when the therapy involves lowering of the blood pressure. Compared with measurement of limb temperature, aortic velocity observations give much earlier indication of haemodynamic changes.

The product of the area of systolic complexes and the heart rate, or - a 'direct equivalent - the mean (time-averaged) blood velocity, gives an index of blood flow in any one patient. To a good approximation, the ratio of serial flow values in the descending aorta equals the ratio of observed mean blood velocities 9), 13). Under most circumstances, this also equals the ratio of serial cardiac output values. In very low output conditions, however, when the autoregulation of the cerebral autoregulation is intact, TAV observations become a more sensitive indicator of changes in cardiac output 9). The only known exception to the reliability of serial blood velocity observations as a guide to circulatory changes are conditions in which the proximal aortic tract is progressively compressed. This will affect the otherwise stable transverse velocity profile in the individual subject, so that blood velocity observations over a period of time would no longer be comparable 15).

In addition to changes in mean flow velocity, changes in waveform details are also significant: Peak velocity and often flow-time ratio (ratio of systole to cardiac cycle period) give a good indication of changes in a patient's condition and are readily assessed by inspection.

In addition, systolic acceleration, an index of contractility of the left ventricular myocardium, can be obtained from the recordings, but requires careful interpretation: An increase in acceleration may be the result of improved left ventricular function or of increased sympathetic stimulation, the latter often indicating in-

creased 'stress' and deterioration in severely ill patients 13). These alternatives can however be resolved by attention to other aspects of the waveform, particularly the flow-time ratio.

Compared with invasive methods, TAV has the advantage of being usable from admission - without delay for the placement of catheters - right through to long term follow-up. During the period of active treatment 16), 17), 18), the availability of immediate feed-back on its effect on blood flow widens the range of therapeutic options. Thus blood volume manipulations, the effect of which is difficult to assess a priori, may be undertaken and optimised in the light of the circulatory response.

The effect of lowering the blood pressure can similarly be observed and settings of pacemakers and positive end expiratory pressure in ventilators can be optimised. Drug dosage may be titrated (fig. 4) and the most favourable of alternative agents (e.g. anti-hypertensive, anti-arrthymic) may be chosen in the light of the individual response.

*Limitations*

With the grey-scale spectral display provided, artefacts are readily recognised and seldom seriously impair the usefulness of the recording. The main limitation of the technique is that a small minority of patients, including those in whom a tracheostomy interferes with transducer placement, give inadequate signals. An oesophageal transducer 21) should offer a modestly invasive alternative when the transcutaneous approach fails.

*Other applications of TAV*

Other clinical uses exist for the instrumentation, which is in essence a direction-resolving Doppler system with deep penetration and high rejection to tissue movement artefact: Obstructive disease in the aorto-iliac segment can be detected by comparison between the velocity waveforms in the abdominal aorta and femoral arteries, while the nature of flow can be observed in the portal vein and inferior vena cava. From the suprasternal notch, signals can also be obtained from the ascending aorta, but in the absence of range-gating they can be difficult to resolve from the similarly directed branch artery flow. Although the ascending aorta is apparently the vessel of first choice for Doppler observations of cardiac function, this site has a number of practical disadvantages compared with the transverse aorta: the flow pattern tends to be relatively complex (e.g. the vortices in the sinuses of Valsalva), the pressure on the transducer needed to direct the beam behind the sternum is often uncomfortable for the patient, and - perhaps most important - it is not usually possible to obtain the nearly in line approach to flow, which is required for quantitative velocity measurements. Much of the potential of non-invasive blood velocity observations in the deep thoracic and abdominal vessels is still unexplored, and new applications are likely to emerge.

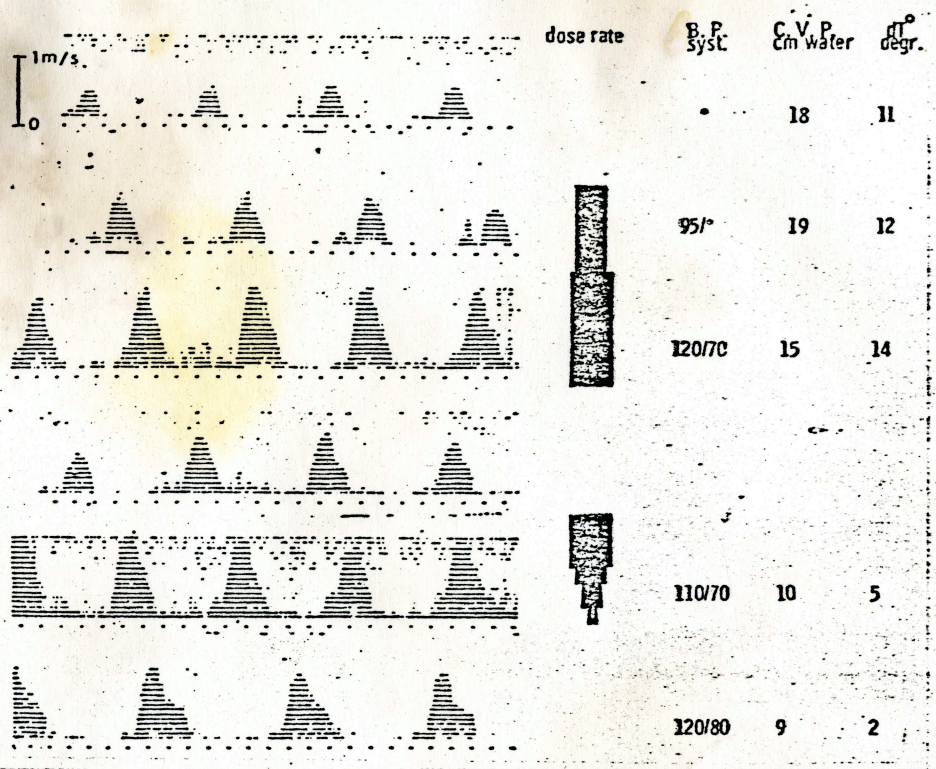


fig. 4. TAV in patient management - titration of drug dosage. Serial TAV measurement on a patient admitted in a moribund condition with barbiturate overdose (1st trace). Intensity of therapy (predominantly by isoprenaline) is indicated by the width of the black bar. The infusion was temporarily stopped after 3 hours to determine the degree of circulatory recovery (4th trace). Subsequently the infusion rate was repeatedly adjusted so as to maintain a roughly normal-looking record. Therapy was discontinued after 7 hours when clinical recovery had taken place. The last recording was obtained 30 minutes later. Readings of blood pressure (systolic/diastolic), central venous pressure and temperature difference between toe and rectum taken at the time of the TAV recordings are also shown. The haemodynamic effect of blood volume manipulation, pacemaker or respirator settings can similarly be observed by this non-invasive technique.

*Conclusion*

A number of trials have shown that TAV offers a quantitative and reproducible non-invasive technique for measuring phasic blood velocity in the aorta. Experimental evidence also supports the theoretical expectation that - in the absence of progressive aortic distortion - such blood velocity measurements give a reliable and reasonably accurate index of body perfusion and left ventricular function. Many forms of malfunction (including hyperdynamic and hypodynamic conditions) and abnormalities of the left ventricular outflow tract are readily detected on inspection of the waveform, while changes give quantitative evidence of disease progression or

the effect of therapy. The technique is easily learned and simple to use on the majority of patients. In clinical trials it was found to give information of value in initial patient assessment, in the monitoring of trends and in guiding effective treatment.

*Acknowledgements*

I am grateful to the many clinicians who have contributed their experience with Transcutaneous Aortovelography, in particular Drs. Gillian Hanson and Anna Buchthal from whose work in Intensive Care fig. 4 is taken, and Dr. R.F. Sequeira who provided some of the pathological waveforms in fig. 3. The help of Geoff Cross has been crucial in the development of the instrumentation.

## References

1) Cross G, and Light LH: *Direction-resolving Doppler instrument with improved rejection of tissue artefacts for transcutaneous aortovelography.* J. Physiol. 217, 5-7 P, 1971.

2) Light LH, and Cross G: *Cardiovascular data by transcutaneous aortovelography.* In Blood Flow Measurement, pp. 60-63. Ed. by C. Roberts, Sector, London, 1972.

3) Cross G, and Light LH: *Non-invasive intrathoracic blood velocity measurement in the assessment of cardiovascular function.* Bio-Medical Engineering, 9, 464, 1974.

4) Light LH: *Non-injurious ultrasonic technique for observing flow in the human aorta.* Nature 224, 119-1121, 1969.

5) Sainz A, Roberts VC, and Pinardi G: *Phase-locked loop techniques applied to ultrasonic Doppler processing.* Ultrasonics 14, 128, 1976.

6) Huntsman LL, Gams E, Johnson CC, and Fairbanks E: *Transcutaneous determination of aortic bloodflow velocities in man.* American Heart Journal 89, 605, 1975.

7) Angelsen BAJ: *Analog estimation of the maximum frequency of Doppler spectra in ultrasonic blood velocity measurements.* Report 76-21-W, Division of Engineering Cybernetics, Norwegian Institute of Technology, University of Trondheim, 1976.

8) Light LH: *Initial evaluation of transcutaneous aortovelography.* *Cardiovascular* Applications of Ultrasound, p. 325. Ed. by R.S. Reneman, North Holland, Amsterdam, 1974.