TECHNICAL NOTE

FLOW RESPONSE OF AN AMPEROMETRIC ELECTRODE

1. INTRODUCTION

A polarised platinum electrode, situated in the blood stream, has been used to record local ascorbate-ion concentration for cardiovascular diagnosis in a technique analogous to the dye-dilution method. The increase in electrode current is proportional to the ascorbate concentration near the electrode, but the current is also sensitive to local blood flow—an "artifact" first noted by the Americans (PFAFF, FROMMER and MORROW) when reporting the method in 1960.

A possible clinical application of the latter effect was reported recently by NIXON et al (1963). Whilst recording dilution curves in the pulmonary artery, the time relations between the pulsatile pressure and ascorbate-electrode current were observed to vary from patient to patient. A correlation with the elastic condition of the lung tissue was suspected, the changes in pressure and electrode current being more close in time as the fibrosis increased. This could be explained if it were assumed, first that the electrode current were a function of flow, and second that the variations in timing between pressure and flow were the results of differing conditions of elasticity in the lung tissue.

For investigating this arterial pressure-flow relation in the circulation, an assessment of the electrode flow response was required. This has been started using a system to simulate pulsatile flow of variable frequency and this paper is a report of some preliminary work.

2. APPARATUS AND METHOD

An approximation to pulsatile flow in an artery was obtained with a similar system to that shown (Fig. 1), by passing saline from a pressurised supply through a tap constriction into a short length (14 cm) of wide-bore (18 mm) flexible pipe and then through a length (100 cm) of comparatively narrow bore (2.5 mm) plastic outlet-tubing to an open sump. Rhythmic compression of the wide pipe was obtained by gripping it between an eccentrically-mounted roller bearing and a rigid support. Because of the constriction in the connection from the supply, the fluctuations in pipe volume produced an alternating flow, most of which passed through the outlet tubing. A superimposed steady flow from the supply could be made sufficient to prevent flow reversal and to give a pulsatile forward flow. The eccentric roller was driven by an electric motor through a variable gear system at a rate of 6-50 cycles per minute. The pulsatile frequency and flow were determined from the pressure drop along a central fraction (20 cm) of the narrow tubing, using a differential manometer. (As will be described later, it was found necessary to apply corrections to this measurement for a true indication of flow.)

In clinical use the electrode is a platinum wire or bead or the platinum annulus of an electrode catheter. Current then flows between this small probe electrode in the blood stream and all the surrounding tissue. Since the plastic tubing was non-conducting, these experiments conduction was between a platinum-wire electrode passing through the tube-wall and one of the metallic T-piece connections. The electrode polarisation voltage was obtained from a constant potential amperometric unit (HAY, HEPBURN and NIXON, 1963). This was designed to give a conveniently-large signal voltage output which was proportional to the electrode current and was recorded together with the manifold output using a Sanborn direct-writing instrument.

Initially the electrode response was obtained at a single frequency, investigating first purely alternating flow, then with various values of steady flow added to reduce or prevent flow reversal. Subsequent experiments were performed at various frequencies in the available range.

3. RESULTS AND DEDUCTIONS

3.1. Response of the flow-monitoring method

Use of the pressure drop for monitoring flow has proved most useful. Serious deficiencies of the method are, however, worth some mention, although they do not render the deductions invalid. The electrode response to purely alternating flow at 18 c/min is illustrated in Fig. 2. This shows features of the electrode response and of the flow-monitoring technique. Firstly, the electrode is very obviously unable to distinguish between forward and reverse flow, despite the asymmetry of electrode geometry. Its behaviour is analogous to that of a full-wave rectifier. Secondly (a criticism of the flow monitor) the variations of electrode current, due to the alternating fluid flow, lag behind those of the pressure differential which is being used to monitor the flow. A delay of about 0.2 sec is seen in the responses and in the region of zero flow the corresponding values of current and pressure are critically dependent upon the correction. The defect is due to neglect of the acceleration of the oscillating fluid in the "flowmeter" and the tentative assumption that the pressure drop was wholly used in overcoming the viscous drag and so could be used to indicate flow.
This was not so in the present case and corrections must be applied when calculating true flow from the recorded pressure drop.

In the system used the acceleration component of the pressure drop was of significant magnitude. Since it has a quadrature phase-lead relative to the velocity or viscous-drag component, the resultant total pressure has a small phase lead relative to the flow of about 20° in this case. Thus in using the pressure differential for monitoring flow, a phase correction was found necessary. In general this correction is dependent upon the pulsatile frequency and if large, indicates a significant reduction in the appropriate amplitude conversion factor relating pressure drop to flow. For the above conditions, later evidence showed that the pressure drop was a valid measure of flow when the observed phase correction alone was made.

### 3.2. Amplitude response to pulsatile flow
In cardiological work, pulsatile rather than alternating flow exists and it is more realistic to examine the behaviour of the system under these conditions. When a steady-flow component was included, the range of flow was extended, the critical effect of the rapid approach to zero-flow was avoided and a definite non-linearity of the amplitude response was revealed. With the decreasing steady component shown (Fig. 3) the maxima and minima of the pressure drop and corresponding electrode currents gave a unique response curve. This confirms the negligible effect of the acceleration component of the pressure drop on the magnitude of the pressure-flow amplitude conversion factor at 18 c/min. At greater pulsation rates this was not so. Using the minimum current as the reference level and points from the smooth response curve, a plot of the square of the current increase against flow gives a good linear relation, showing the current increase to be proportional to the square root of the flow under these conditions. The form of this relation is the same as that presented by Levich (1944) for a simplified electrode and moving electrolyte system, for which a full calculation proved possible.

#### 3.3. Temporal dependence of the response
The delay of the electrode current response relative to the pressure drop when approaching zero flow was found to be greater than at other times. The minimum electrode currents at the start of small reverse flow were found to be consistently less than when large reverse flow occurred. Moreover, when small reverse flow started, the current minimum was not so small as when it ceased. These observations are all results of a delayed response to low-flow conditions.

For purely alternating flow at the higher frequencies, the zero-flow condition is approached more rapidly giving correspondingly decreased fidelity of the electrode current response. This is illustrated in Fig. 4, where the inadequate response to the more rapid flow reversal is very marked. Since the pulse generator approximated to a constant displacement unit, the resultant flow magnitude increased with frequency and the rate of approach to zero flow increased roughly as the second power of the frequency. This causes the exaggerated display of the effect. The response is closely similar to that of an electronic rectifier circuit, with only a little output smoothing present. Slight smoothing prevents an immediate output response to an instantaneous drop of input voltage, but is ineffective in producing distortion of a slowly-varying input. Comparison with the behaviour of the analogous full-wave rectifier circuit indicates an effective smoothing time constant of the order of a second in the electrode system tested.

On increasing the pulsation frequency with various steady components present, similar response curves were obtained. The electrode current response to pulsations of various frequencies in the presence of a large steady flow (which is always sufficient to prevent flow reversal) is shown in Fig. 5. This illustrates the more immediately-useful application of the effect, when any approach to flow reversal is avoided. Under these conditions significant delay is absent and the electrode response is substantially linear.

### 4. CONCLUSION
Where there is no approach to zero flow, there are two significant advantages. Firstly, with avoidance of low-flow conditions, the distortions due to the deficient response to a rapidly decreasing flow are reduced. Secondly, the electrode amplitude response becomes more linear. In a practical situation, if the flow is never less than 25% of maximum, deviations from linearity are less than 5%. Under these circumstances the electrode effect may prove a most useful indicator of the waveform of pulsatile flow in the circulation.