A SENSITIVE AND STABLE EARPIECE FOR DYE DILUTION CURVES

BY

JOHN NORMAN

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The measurement of cardiac output, from the study of the concentration of a circulating dye against time, has in the past been most commonly carried out using whole blood cuvettes (Friedlich et al., 1950; Falholt and Kaiser, 1955; Shadle et al., 1953; Nicholson et al., 1951). At a wavelength of 640 millimicrons the density of arterial blood flowing at a constant rate between the photo-cells and light source is continuously recorded, and the curve calibrated for dye concentration by the analysis of a single sample taken after the dye is evenly distributed, or the analysis of an aliquot of the blood collected throughout the inscribed curve (Emanuel et al., 1957). Qualitative assessment of intra-cardiac shunts has also been carried out during cardiac catheterization using similar procedures (Swan et al., 1953; Broadbent and Wood, 1954). The growing importance of this type of dye curve has stimulated interest in the substitution of a reliable earpiece for the whole blood cuvette, where the primary need is for a series of dye curves from the various chambers and great vessels carried out in rapid succession. While linearity of the earpiece in this application is of lesser importance than stability and high sensitivity, it is an advantage if the resulting curves can be used quantitatively where necessary. A number of earpieces have been previously described in association with apparatus for measuring the arterial oxygen saturation in the heat flushed ear (Millikan, 1942; Wood, 1950; Stott, 1953; Milnor et al., 1953) and these have been used for the continuous recording of the arterial concentration of Evans Blue.

The continued use of whole blood cuvettes, necessitating arterial puncture and the withdrawal of considerable quantities of blood when serial curves are recorded, is to some extent a reflection of the difficulties that have been experienced in the design of accurate earpieces.

The instability of dye-measuring earpieces at the sensitivity at which it is necessary to use them has always been a problem. It arises from four main causes: (a) the necessity for high gain D.C. amplifiers as a result of the extremely small electrical output from the earpiece, (b) movement of the earpiece independently of the ear, (c) volume changes occurring at the ear as a result of peripheral arterial pressure changes, and (d) "thermal drift," due either to inadequate initial vasodilatation or to the heating of the photo-cells themselves when measurements are prolonged. In instruments that use barrier layer photo-cells, deterioration of the sensitive surface as a result of the effect of harmful vapours has in the past prevented a sufficient long-term stability for the accurate comparison of dye curves recorded over a long period of time.

This paper describes an earpiece designed specifically for the accurate recording of dye curves for qualitative and quantitative purposes. Using the principles outlined in an earlier paper (Norman, 1959) many of the criticisms of the use of earpieces for this work have been effectively met, and the unit is both linear and stable. Since almost all dye curves are recorded with the patient supine, there seemed at the outset to be no point in attempting to make the instrument very small, for, provided that the actual attachment to the ear is of convenient size, the dimensions and shape of the rest of the earpiece are not material. As will be seen, this view has produced a unit that is large by

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present standards, but one where the size permits the incorporation of systems designed to avoid the difficulties of instability described.

The electrical output from the earpiece itself, which uses a 16 watt light source, is sufficient to feed directly into the recorder amplifier, and the large change in signal produced by the dye injection ensures an extremely high "signal/noise" ratio. Because of the size of the light source, air cooling is used to maintain the whole unit at body temperature, and the earpiece may be left in position for six hours or more without ill effect.

Objections to the use of barrier layer photo-cells have been over come by sealing the infra-red and red sensitive cells in a block of resin. The leads are soldered to the sprayed-on contact surfaces of the photo-cells before embedding, and are brought out through a moulding at the side of the resin block (Fig. 1). This produces a completely airtight assembly and prevents the effects of harmful vapours on the sensitive surfaces of the cells. Short-term instability, or "flicker," often due to the spring devices previously used to obtain electrical contact has been entirely eliminated, and the sealed photo-cell unit may be subjected to severe vibration without intermittency of this nature arising. A further advantage of this type of cell assembly is that the relative position of the two cells is fixed.

**CONSTRUCTION**

The body of the earpiece (Fig. 2) is formed from black perspex block, and is machined to form a cylinder 4-5 inches long by 1-75 inches O.D. A wall of 0-375 inches leaves an internal bore of 1 inch. At a point 1-5 inches from one end a smaller tube of O.D. 0-75 inches is set into the wall at right angles to the long axis. The outer end of this smaller tube is faced with 1/16 inch perspex (J) and forms the window of the light source.

At the same end of the cylinder a disc carries a single contact batten holder for a pear-shaped 16-watt bulb (C). Opposed pins fitted to this disc engage with the low tension sockets (F) in the body of the earpiece. A perspex plate closes this end of the unit (G). At the upper end of the cylindrical body (E) an end cap carries a six pin Mk IV socket (A) from which the supply to the light source is carried through the wall of the cylinder to the low tension sockets. From this Mk IV socket the three wires to the photo-cell block are also carried through the wall of the earpiece body.

Two Luer taper female entries (B) connect with airways in the wall of the unit, and carry the cooling air (H) directly to the perspex face in contact with the ear, and the exhaust air (D) from behind the light source out to the atmosphere.

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**FIG. 1.—Diagram of sealed photo-cell assembly, showing (A) epoxy resin block, (B) red sensitive cell, and (C) infra-red sensitive cell.**
In Fig. 3 may be seen a plan view of the earpiece with the upper end plate removed, and from this it may be seen that the photo-cell housing, which also serves to attach the unit to the ear, is fitted to the body of the unit by a knurled nut (G) on a 2 BA stud. The side arm of the photo-cell housing is formed with a short oval slot, and the necessary degree of movement of the photo-cell housing relative to the perspex window (B) is effected by movement of the slot over the stud. The maximum ear gap (E) is 0.5 inch.

Beneath the 1/16 inch perspex cover of the photo-cell housing are set the infra-red (Ilford 207) and red (Ilford 205) gelatine filters (D), and behind them is the epoxy resin block containing the red and infra-red photo-cells (A). The three wires from this unit are taken down the hollow side
arm of the cell holder, and pass through an oval hole into the wall of the earpiece (C). The length of this oval hole ensures that the wires are not damaged when the photo-cell block is moved relative to the light source window.

At (F) may be seen the short stub and its connection which brings the inlet air as close to this window as possible. A five-way cable is formed as part of a polyvinyl chloride tube having three channels. The other two channels carry the cooling air to and from the unit, and are terminated in male Luer tapers which match the tapers in the end plate of the unit. The output from the earpiece is taken to the matching unit previously described (Norman, 1959) and thence to a high speed Honeywell Brown Chart Recorder with a maximum deflection of 280 mm. A second signal channel is fitted to this recorder and the moment of dye injection is signalled, either manually or by an automatic dye syringe. The complete earpiece with airlines attached may be seen in Fig. 4.

![Earpiece with air lines and cable form attached.](image)

**FIG. 4.—** Earpiece with air lines and cable form attached.

**PERFORMANCE**

Stability of the instrument has been confirmed at the sensitivity at which it is used, while excluding possible variation in a subject, by the use of a neutral density filter, representing the bloodless ear, and two thicknesses of Ilford 205 gelatine filter, representing the blood content in the flushed ear. This assembly is interposed between the light source and the photo-cell housing, and produces the same balance position and sensitivity on the recorder as is produced when the earpiece is transferred to the flushed ear of a normal subject. Using this “artificial ear” for timed stability recordings, it is possible therefore to relate the drift to its equivalent in terms of mg./l. of Evans Blue.

Over a two-hour period the maximum deviation recorded on the instrument described is 1·0 mg./l., while ten-minute periods show maximum deviations of the order of 0·3 mg./l., Evans Blue.

Using cooling air at a flow rate of 10 l/min., the temperature of the body of the earpiece after two hours is 36° C., and that of the photo-cells 25° C., when the ambient temperature is 21° C. It will be seen that even very long periods of use will not appreciably raise the temperature of the photo-cells, and the mass of the earpiece ensures a long heating/cooling cycle. Maximum sensitivity is of the order of 0·3 mg. Evans Blue/l. (whole blood)/cm. deflection.
Confirmation of the linearity of earpieces used for dye dilution work is not an easy matter, since any instrumental substitution for the ear may introduce factors not present when the earpiece is used on the heat-flushed ear. It was thought desirable that the linearity of the apparatus should be confirmed if possible under the circumstances of normal use, since this is the situation in which much deviation from linearity would cause the greatest error if the unit were used quantitatively.

Additions of equal increments of Evans Blue to the circulation will raise the background level of dye progressively, and dye-measuring instruments that are not linear will show variations in the indicated peak concentration and equilibration levels, if repeated dye injections of equal amounts are made against this rising background.

This was the method used for the earpiece described; repeated injections of 10 mg. of Evans Blue were made into the same site in resting subjects with no intra-cardiac shunts, and the identical indicated peak concentrations, measured as a function of deflection, confirmed that the linearity of the unit is satisfactory for quantitative work.

An example of the accuracy with which curve shape may be reproduced following injections into the same site may be seen in Fig. 5; this illustrates the second and third injections out of a series of four made into the left pulmonary artery. It will be seen that in spite of the rising background of dye concentration the peak deflection is identical in both curves.

It will, however, be clear that against a progressively increasing level of dye in the circulating blood some loss of sensitivity for each successive dye injection must ultimately ensue, since the increment of dye must be less easily detectable against a blue background than against a red one. That this is true may be seen from the low amplitude dye curves obtained when using a blue dye in patients with central cyanosis. It is possible to maintain a broadly linear function using the earpiece, only because the total absolute density of dye in the blood, after the maximum number of injections that may be cosmetically acceptable, is still low when compared with the injected dye.

**Comment**

In spite of the size of the earpiece, no difficulty has been experienced in fitting it routinely to the pinnae of adults, and to those of children down to the age of about four years. A smaller unit is being developed for use with infants from birth onwards.
It has been our practice to massage the ear with a rubefacient cream ("Trafuril," Ciba, Ltd.) some fifteen minutes before the investigation starts and to remove the cream by brisk massage with a dry towel immediately before applying the earpiece. No difficulty has been experienced in ensuring that the ear is left fully flushed, since the edge of the clear perspex cover of the photo-cell housing gives a ready indication if blanching occurs. The earpiece is applied with just sufficient tension to hold it in place with no discomfort to the patient.

Because the length of the light path is fixed, and no spring devices are used to fix the unit to the ear, arterial pulsation artefacts, which are due to alterations in the light path length caused by volume changes in the ear, are not seen when using this earpiece.

**SUMMARY**

A highly stable earpiece for dye curves is described. Large by present standards, the unit uses cooling air to maintain it in thermal equilibrium while keeping the heated ear fully blood flushed. A high intensity light source is used to produce a large change in output from the photo-cells, and this may be taken directly to the recorder amplifier. A high "signal/noise" ratio is thus obtained. The photo-cells themselves are hermetically sealed in an epoxy resin block, a method that ensures excellent short and long term stability.

The overall sensitivity is such that central injections of 5 mg. of Evans Blue or equivalent amounts of other dyes will produce deflections of up to 25 cm. on a wide chart recorder.

A simple matching unit provides for sensitivity and balance controls, and effects the circuit changes that are necessary when using Cardio-Green.

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**REFERENCES**

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John Norman

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