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TECHNICAL NOTE

Photoelectric measurement of blood flow during hemodialysis

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Accurate measurements of blood flow rate during hemodialysis are essential for determinations of hemodialyzer performance. Despite the availability of a variety of electronic blood flow meters, use of such instruments for determination of blood flow in hemodialysis has never been satisfactory, a situation caused by such factors as the need to recalibrate frequently, the necessity of incorporating transducers into the dialyzer blood circuit and the effect which variables such as hematocrit may have on the accuracy of determination. Furthermore, such devices are expensive and often require the periodic services of an electronics specialist to maintain them in an operable condition.

An alternative technique for measuring flow rate in the extracorporeal blood tubing consists of timing the passage of an injected air bubble between two points in the tubing. Since the advent of maintenance dialysis, the "racetrack and bubble time" technique [1] has been widely used for routine determinations of blood flow rate. Data derived from research studies in which this method of flow determination was employed have been published widely, in spite of the relative inaccuracies of the method.

In a previous report [2] the influence of variables such as hematocrit and bubble size was studied, and a revised calibration chart relating bubble transit time to blood flow rate was presented. During this study it became apparent that the greatest source of error is attributable to human factors, such as perceiving the instant at which the injected bubble enters and leaves the racetrack and coordinating these two events with the starting and stopping of a stopwatch.

Recognition of this problem led to development of a convenient and inexpensive portable bubble timer (Fig. 1) which eliminates operator error. The timer, which operates from photoelectric triggers and can be operated by unskilled persons, is accurate to ±2%.

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The timer employs a light source beamed transversely across a loop of blood tubing that constitutes the racetrack and two tunnel diode triggers coupled to phototransistors (Fig. 2). The light source illuminates both start and stop locations on the racetrack, which is usually 50 cm in length. The light-sensitive areas of both phototransistors are normally darkened by blood contained in the tubing between light source and transistors.

When an air bubble is injected into the tubing, first one, then the second phototransistor are illuminated momentarily, since light transmission across the bubble is greater than in the blood. The increased light level produces an increased current flow through each phototransistor, which is amplified by an emitter follower, in turn controlling current to the tunnel diode and to the output transistor base. This signal is employed to activate a digital counter on which bubble transit time is registered.

Before use, the digital counter is reset to zero by hand, causing the tunnel diode to go to its lowest impedance state and the output transistor to be biased off. When an injected air bubble passes the start location, the increased current flow through the phototransistor causes the emitter follower current to increase to the peak point current of the tunnel diode, where the latter switches to its high impedance state. The resultant rise in voltage allows the output transistor base to draw current and thus turn on the transistor. As the bubble arrives at the start location and the transistor senses the increased light level, the negative going signal at the output transistor collector is used to trigger the electronic counter to begin counting. Moments later as the bubble passes the second phototransistor at the end of the racetrack, the signal sequence is repeated to stop the counter. The time registered on the counter represents the "transit time" of the air bolus along the measured tubing segment. By reference to a calibration chart the transit time readily can be converted to volume flow through the tubing (Table 1).

The electronic clock contains a 1000 Hertz oscillator, a start, stop and reset gating circuit, a four decade counter

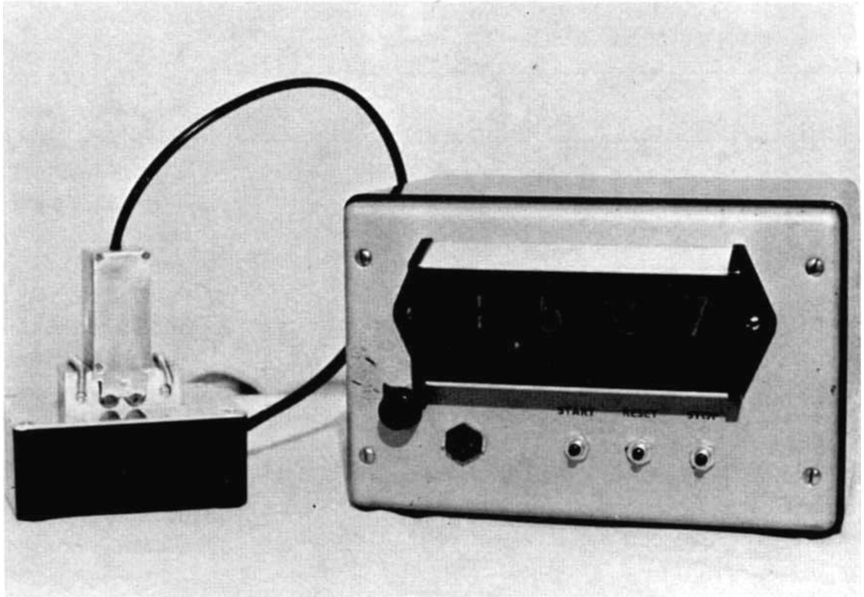

Fig. 1. *The portable timer system includes an electronic clock with digital display at right.* The block at left contains recessed channels for blood tubing and the light source.

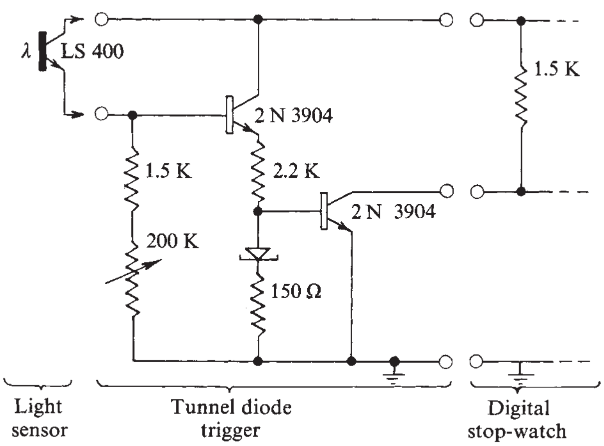

Fig. 2. *Circuit diagram of the bubble timer.*

with readout and a power supply. Arrival of the negative going impulse at the start input opens the gate between oscillator and decade counter. Each oscillator pulse is counted by the decade counter until the gate is closed by arrival of a negative going pulse at the stop input. Front panel push buttons are provided to start and stop the clock manually if desired. A third push button is provided to reset the clock to zero prior to timing.

In Table 2 the % errors in blood flow measurement obtained by several staff members using both the electronic timer and a hand-held stopwatch are compared. Accuracy of the two methods was established by comparison of timer and stopwatch measurement against control values obtained by volumetric collection of whole human blood at flow rates from 50 to 500 ml/min. From the table it can be seen that measurements using the stopwatch are less consistent and have a wider range of error than do measurements obtained with the photoelectric timer.

Table 1. Blood flow determination by bubble time[a]
50-cm Racetrack

Time *sec*	Flow rate *ml/min*	Time *sec*	Flow rate *ml/min*
0.6	600	2.5	170
0.65	564	2.6	163.5
0.7	530	2.7	157
0.75	501	2.8	151
0.8	473	2.9	145.8
0.85	445	3.0	140.8
0.9	420	3.1	136.3
0.95	398	3.2	132
1.0	379	3.3	128
1.05	361	3.4	124.8
1.1	346	3.5	121.4
1.15	334	3.6	118.2
1.2	322	3.7	115
1.25	311	3.8	112.3
1.3	301	3.9	109.5
1.4	284	4.0	107
1.5	270	4.1	104.5
1.6	257	4.2	102
1.7	245	4.3	100
1.8	233	4.4	97.5
1.9	222	4.5	95
2.0	212	4.6	93
2.1	202.5	4.7	91
2.2	193.7	4.8	89
2.3	185	4.9	87
2.4	178	5.0	85

[a] Calibration obtained at 37°C with whole human blood using roller pump and $\frac{1}{8}$-inch I.D. pump tube.

While use of the timer described herein makes possible more precise determination of blood flow through elimination of the human error factor, the user seeking a high degree of accuracy must be aware of other factors which influence accuracy of flow measurement. Observations by

Table 2. Error with hand-held stopwatch and electronic timer based on volumetric blood flow measurement

Observer	Stopwatch % error	Electronic timer % error
A	−2	−0.3
B	+6	+1
C	−7	+1
D	−4	−2
E	+3	+2
F	−14	+1

All timed measurements performed on 50-cm racetrack with whole human blood, at 37°C. Blood flow controlled by roller pump using ⅛-inch I.D. pump tubing.

the authors have shown variations of as much as 4% in racetrack length as marked on the tubing by the manufacturers. Consequently, it is suggested that track length be verified prior to flow measurement and corrected if necessary. This can be done either before or during dialysis, as track length is not affected by change from ambient to body temperature.

A second factor that can cause variations in flow measurement is the inside diameter of the blood pump tubing. In the studies described above pump tubing with an I.D. of ⅛ inch was employed in order to minimize error introduced by pulsatile flow. When pump tubing larger than this is used, an additional error may be introduced, since stroke rate is slowed and stroke volume increased for a given flow. With larger-diameter tubing the time at which the bubble is injected relative to the stroke of the pump may cause considerable scatter in the measured bubble transit time. Differences of as much as 8% in measured flow have been noted using pump tubing with an I.D. of ¼ inch in conjunction with a 50-cm racetrack. Measurement accuracy can be improved considerably when tubing length permits use of a longer racetrack, since any variation in the timing relationship between bubble injection and stroke becomes an increasingly smaller increment of total transit time. For example, when ¼-inch I.D. pump tubing is used, measurement differences are held to within approximately 4% with a 100-cm track, and to 2% with a 200-cm racetrack. Consequently, it is suggested to those who prefer to use larger-I.D. pump segments that they prepare their own calibration chart using the longest racetrack length permitted by design of the blood tubing set.

A third variable which may affect measurement accuracy is that of differences in inside dimensions of the racetrack tubing. One might expect tubing bore to change as internal pressure varies according to dialysis conditions; however, the effects of internal pressure appear to be negligible at normal operating pressures. In flow studies at pressures from 10 to 250 mm Hg flow readings were not affected by internal tubing pressure. We have noted, however, that the inside dimension of tubing sets can vary by at least 2.5% because of manufacturing tolerances. In the rare instance where extreme accuracy is desired, it is suggested that the racetrack to be used be calibrated and a correction for dimensional variation employed.

It should be noted that there are many different circuit designs which can be employed to operate a photoelectric timer for this application. That described was selected because it can be constructed from readily available components which cost less than $350.00 and can be assembled by persons with general electronic experience. An estimated ten hours of assembly time is required.

In prior studies [2] we have shown that measurement accuracy using the injected bubble technique is principally affected by human error. When computing dialyzer performance, error introduced by human factors may be significant, especially at higher blood flow rates. Use of the timing principle described herein reduces such error; because of its convenience it has been accepted readily for routine use by staff personnel. No mechanical or electronic problems have occurred in over three years of almost daily use. Furthermore, the minute or two required to prepare the system for use is less than the time usually required to locate the typical migratory stopwatch resting in the pocket of the previous user.

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