The hazard of electrocution during patient monitoring

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Summary

The ever-present hazard in patient monitoring is electrocution resulting in ventricular fibrillation. Fire and explosion hazards are possibilities but seem to be very remote.

Iatrogenic electrocution can occur when:

(a) more than one piece of electrical equipment is connected to the patient.
(b) the distal end of an intracardiac electrode is handled.
(c) pericardiocentesis is carried out with ECG monitoring.

Under these circumstances, small currents, of the order of 100–200 μA, may cause ventricular fibrillation. There is evidence that the ventricular fibrillation threshold is substantially lowered by anoxia and acidosis but it seems to be unaffected by barbiturate anaesthesia.

This paper suggests that the physician or surgeon should understand the risks but may need the expert advice of an electrical engineer. Ventricular fibrillation which has occurred under these circumstances requires careful, expert investigation to establish whether or not it was electrically induced.

Introduction

The installation of several pieces of electronic apparatus at the patient’s bedside may give rise to a number of hazards. Fire and explosion, from the ignition of anaesthetic gases, are obvious possibilities, but, because they are obvious, they are well guarded against and are very remote (Dobbie, 1969, personal communication). On the other hand, accidental electrocution of patients has been reported on a number of occasions. It will be seen how small are the electric currents which may cause ventricular fibrillation under the circumstances of patient monitoring.

If anyone touches a conductor carrying an alternating current at mains frequency, 50 Hz, an immediate tingling or throbbing is felt. The threshold for this effect is about 1 milliampere (mA) (Conrad, Haggard & Teare, 1936; Dalziel, Lagen & Thurston, 1941). A much larger current, about 100 mA, passing between the right arm and the legs, may cause ventricular fibrillation (Dalziel & Lee, 1968). Such a current passes through the body as through a conductor—it neither preferentially follows the blood vessels nor evades passage through the bones (Weeks, Alexander & Dennis, 1939). Thus, as it traverses the thorax, it is widely distributed and the current density (current flow per unit area) is reduced. About 4 or 7% of the total current flows in the region of the heart (Kouwenhoven, Hooker & Langworthy, 1932; Weeks et al., 1939). Furthermore, the ventricles will be put into fibrillation only if the current passes during the relative refractory period following ventricular contraction (Ferris et al., 1936; Wegria & Wiggers, 1940).

Ventricular fibrillation threshold from one intracardiac electrode

If the current is conducted directly to the myocardium, either along an intracardiac catheter or a pace-maker electrode, the current density at the point of contact with the myocardium becomes much greater and fibrillation would be expected to result from small currents. In a review of some of the earlier cases of ‘iatrogenic electrocution’ (Lee, 1964) it appeared that, under these circumstances, currents of only 100–200 μA might cause ventricular fibrillation. Further reports since then have served to confirm this suggestion. Whalen, Starmer & McIntosh (1964) investigated the ventricular fibrillation threshold of patients undergoing open heart surgery, on a cardio-pulmonary bypass and under moderate hypothermia (30–34°C). Using two large electrodes (2.5 cm diameter) applied directly to the heart the currents necessary to induce fibrillation ranged from 1500 to 6000 μA, but with smaller electrodes (0.25 cm diameter) producing a much greater current density, the threshold fibrillating currents ranged from 180 to 1500 μA. Rowe & Zarnstorff (1965) reported on seven cases of ventricular fibrillation occurring during the course of 600 angiograms and considered the likely cause to be ‘an electrical discharge’ of
about 40 volts delivered, for 1–2 msec, from the solenoids to the syringe of the injector. If the resistance of the catheter employed is presumed to be about 300,000 ohms (Starmer, Whalen & McIntosh, 1964; Whalen & Starmer, 1967), then from Ohm’s law the current was about 130 μA. It should be noted that this was a brief, 1–2 msec, pulsed current and not an alternating current. The question whether there would be any marked difference in the ventricular fibrillation thresholds of the two types of current is discussed later.

A number of observers, using mains frequency alternating current, have investigated the minimum fibrillating current in dogs with one electrode connected directly to the heart. There is a good measure of agreement in the results. Weinberg and his colleagues (1962a) found that with one electrode in the left ventricle and one on the chest the minimum fibrillating current, of unspecified duration, was 40 μA, although elsewhere they had reported producing ventricular fibrillation under similar circumstances at only 20 μA (1962b). Whalen et al. (1964) applied shocks of 2 sec duration between an electrode in the left ventricle and another on the chest and found that the minimum fibrillating current was 20 μA. Burchell & Sturm (1967) produced ventricular fibrillation under similar circumstances with currents of about 12 μA, but give no further details.

Factors affecting ventricular fibrillation threshold

Anaesthetic agent. The investigations described above were conducted on dogs anaesthetized with sodium pentobarbital. McIntosh, Starmer & Whalen (1966) found that the ventricular fibrillation threshold in a dog anaesthetized with sodium pentobarbital was the same as in the same animal when unaesthetized. There have been no reports of similar comparisons using other anaesthetics.

Acid-base state. Investigations into the effects of the acid-base state on the ventricular fibrillation threshold show that, in general, acidosis lowers the threshold and alkalosis raises it. Gerst, Fleming & Malm (1966) found that the threshold was lowered in metabolic acidosis and raised in metabolic alkalosis. Turnbull & Dobell (1966) showed that both respiratory and metabolic acidosis lowered the threshold, and Dong, Stinson & Shumway (1967) found that respiratory alkalosis raised the threshold. It should be noted that in these three studies the observers used rectangular pulses from 2.5 to 13 msec in duration, and not alternating current, to produce fibrillation and they applied both electrodes directly to the heart. There is no reason to expect that qualitatively different results would be obtained if alternating current were used although the actual current values might be different. The magnitude of some of these changes in threshold may be illustrated by reference to some of the results of Gerst and his colleagues. In a control experiment with a blood pH of 7.38, PCO₂ of 40-4 mmHg and a base deficit of 2.2 mEq/l the ventricular fibrillation threshold was 9 μA. This fell to 5.4 when metabolic acidosis was produced in the same animal (pH 7.06; PCO₂ 39.5 mmHg and base deficit 20.2 mEq/l).

Iatrogenic electrocution

There are a number of case reports describing in some detail the circumstances under which iatrogenic electrocution has occurred and several papers discussing, theoretically, the circumstances which might predispose to such an accident. Review of these accounts (Burchell & Sturm, 1967) suggests that, according to the circumstances, such accidents may be grouped under three headings:

1. More than one piece of electrical equipment employed in patient care.
2. Handling of the distal end of an intracardiac electrode.
3. Use of electrocardiographic monitoring during pericardiocentesis.

These situations will now be considered in further detail:

1. More than one piece of electrical equipment employed in patient care

Although this cause of ventricular fibrillation was foreseen and reported as long ago as 1960 by Zoll & Linenthal, it remains the one which recurs time and again in reports in the literature. In 1961, Furman and his colleagues reported three deaths, all from ventricular fibrillation, developing during the measurement of cardiac output during pacing. Investigation revealed minute 60 Hz AC leaks via the pacemaker, oscilloscope, recorder and fluoroscope which were interconnected to the mains current and the patient. A careful investigation of an accident with an unearthed power syringe was carried out by Bouvaros, Don & Hopps (1962). Immediately the cardiac catheter, filled with saline, was connected to the power syringe the patient developed ventricular fibrillation. They found an open circuit potential of 79 volts between the case of the syringe and earth. The instantaneous current was calculated to be 415 μA and the steady state current 270 μA. Similar figures were found in Briller’s two cases which were reported by Burchell (1963). Faulty solenoids in a mechanical injector used during selective angiography by Rowe & Zarnstorff (1965) were probably responsible for seven cases of ventricular fibrillation by 2 msec pulses of current estimated, in an earlier section of the present paper, to be about 130 μA. The serious probability of such hazards is revealed in similar reports from Burchell (1961) and
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Noordijk, Oey & Tebra (1961) who found electrocardiographs with leakage currents to earth of 0·64 mA and 1·0 mA respectively.

Hopps (1969) has recently given a clear example of how a resistance as low as 0·01Ω in the earth lead of one piece of apparatus could give rise to a fatal current (Fig. 1). If a fault to earth develops in an apparatus a current will flow from the live conductor to earth through that fault and so long as the current is less than the protective fuse, say 10 amps, it will continue to flow. If the earth connection of the instrument has a resistance of only 0·01Ω, then by the application of Ohm’s law it will be seen that the ‘earthed’ case of the apparatus will have a potential of 100 mV above earth. If this is connected, even via the standby earthed position, to a low resistance cardiac electrode in a patient whose right leg is earthed via an electrocardiograph, the current pathway through the patient might have an impedance as low as 500Ω and so allow a current of 200 μA to pass. Two points can be made, firstly, in this country the limiting fuse should be 2 amps (not 10) and secondly, the figure of 500Ω taken by Hopps as the resistance in the patient is very low by a factor of 2. In these circumstances the leakage current would be about 20 μA; possibly below the threshold of fibrillation.

These hazards arise from leakage of mains alternating current. We should, therefore, consider not only the simple resistive leaks already described but, because alternating current can pass across capacitors, the capacitive leaks which might occur in components or apparatus. If, as will be seen later in this paper, we wish to restrict to 10 μA the leakage current, passing through a patient from the mains supply at 240 volts to earth then from Ohm’s law the total impedance to meet this condition would be:

\[ Z = \frac{240}{10 \times 10^{-8}} = 24 \text{ megohms} \]

the impedance of a capacitor to alternating current is

\[ \frac{1}{2\pi fC} \]

(where f is the frequency of alternation in Hz and C is the capacity). Therefore, the maximum allowable capacitance would be 133 pico-farads.

A much larger figure is usually given for the interwinding capacitance of instrument power transformers unless special construction (i.e. double screening) is used.

(2) Handling the distal end of an intracardiac electrode

The electrode catheter used in the investigation of certain arrhythmias or for other purposes provides a low resistance path to the heart. Stanley (1967) has calculated that the electrical resistance through the body from a catheter electrode on the inside of the ventricle to the earthed electrode on the right leg is about 1000Ω. Normally the electrode catheter is connected to the V lead of the electrocardiograph which incorporates a very high resistance of 5–10 megohms. This resistance serves to limit any current flow which might result if the earth lead develops a slight voltage due to a faulty component.

However, if an attendant touches the catheter (Fig. 2), or it is otherwise earthed, the protection of the high resistance in the V lead is lost and a current sufficient to cause ventricular fibrillation might then flow along the catheter (Starmer et al., 1964). For this reason those authors have suggested that the connection between the electrode catheter and the V lead should be protected with an insulator such as a firmly fitting rubber sleeve.

Danger can also arise, under certain circumstances, from touching the terminal of a myocardial electrode connected with a battery-powered pacemaker. As in

![Fig. 1. Leakage through patient between 'earth' connections of two pieces of apparatus (after Hopps, 1969).](image-url)
the previous example, there is a low resistance pathway to the heart which is normally isolated completely from earth, being connected to a battery-powered pacemaker. No current would flow along this pathway even if a faulty electrocardiograph developed a slight voltage in the earth (Right leg) connection. If, however, an attendant touches the terminal of the myocardial electrode he completes a current pathway to ground along which a fibrillating current could flow.

(3) Use of electrocardiographic monitoring during pericardiocentesis.

In some situations, during pericardiocentesis, the exploring needle is connected to the V lead of an electrocardiograph so that should the needle touch the epicardium the operator is warned by the ECG. In a way comparable with possible electrocution via the intracardiac electrode, a hazard might arise from a badly earthed electrocardiograph. If a needle with an insulated shaft is used this will increase the density of the shock current where the needle tip is in contact with the epicardium and the risk of electrocution will be much greater (Starmer et al., 1964).

Discussion

Various procedures during patient monitoring and intensive care can result in electric currents being led directly to the heart along catheters or needles. Review both of accident reports and of experimental studies suggests that electrocution may occur from very small currents, of 100–200 μA. For this reason certain standards of maximum allowable leakage currents have been proposed in the United States. Neuland (1969) has suggested a maximum safe shock current of 1–10 μA and the Underwriters Laboratories in America (1969) have suggested a maximum permitted leakage current of 5 μA between any patient lead and earth.

Currents of this order are well below the normal threshold of skin sensation, which is about 1 mA, so that an an attendant touching one of the contacts at the time the patient was electrocuted might be unaware that a current was passing. Measuring and devising protective methods against such minute currents is outside the field of training of most medical men and it is therefore strongly advisable to seek the co-operation of persons such as the safety engineers in the Department of Health in this country. In the U.S.A. discussions of safety measures have been published by Hopps (1969) and by Neuland (1969). Furthermore, Burchell, who has written thoughtfully on the subject over a number of years, has recently suggested that 'Any instance of ventricular fibrillation occurring when a patient has a catheter or sound in the heart should be assumed to be caused by electric current until proved otherwise' (Burchell & Sturm, 1967).

References

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