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Electro-Convulsive Therapy with Minimum Hazard

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Summary: The inter-electrode resistance during ECT is shown to be very variable, a finding which invalidates the measurement of shocks in joules. With square wave pulses of selected current value the threshold for convulsion may be below 100 milliamperes or above 2,000 milliamperes. It is advisable to measure the current value during millisecond pulses with relatively long intervals between.

At the Leicester University Conference on ECT in 1979 it was reported (Gordon, 1980) that it was possible by using short square-wave pulses to reduce the current passing through the patient by a factor of about ten without altering the length of the convulsion produced. Experiments in the laboratory and on the cadaver showed that the skull bone had a very great effect in determining the proportion of the electricity that traverse the cranial cavity and the course taken by that current (Gordon, 1981). The location of lacunae and places where the bone is thin has much more effect on the path of the electricity than does the exact point of application of the scalp electrodes.

Since 1979 the design of our (City University) equipment has been modified step by step in the light of experience and though finality has not yet been achieved, the improvements in the measurement of all the electrical factors permits research to be more soundly based.

Research in this field is exceptionally difficult to carry out in a way that will permit statistical proof. In current literature the electrical dose is measured in joules and the general assumption that two patients receiving shocks of say 30 joules will receive similar stimulation to their cerebral cortices. This is certainly not the case.

The available ECT instruments can be divided into two groups. The vast majority in current use, the Ectron Duopulse and earlier Ectron models, the Konvulsator and some others, are based on a transformer at mains frequency giving a constant voltage for a selected time. The sinusoidal waveform is usually modified by semiconductors. The second group which is much less commonly used, is based on the discharge of a capacitor through an interruptor originally mechanical but now electronic. The Theratronics Transpsycon, the Mecta, the Ectron constant current instrument and our City University instruments are of this type.

In the first group the number of joules is calculated on the basis that the inter-electrode resistance is known, so that for a given voltage supplied by the transformer the current will be calculated by dividing the volts by the resistance. Current multiplied by volts gives watts. Joules are watt-seconds so if the calculation gives 15 watts a time of 2 seconds will give 30 joules.

The Table shows the inter-electrode resistance for 18 patients who had three or more resistance measurements made with the latest most accurate City University instrument. The cases are arranged in order of their average resistance but with the individual readings in chronological order. The highest and lowest readings for each patient are underlined.

It will be seen that the 375 ohms assumed by Ectron, the 300 ohms assumed for the Konvulsator and the 250–300 ohms assumed for the Mecta, represent an unjustifiable over-simplification. The exceptionally high reading in Case B.9. of 1360 ohms may be ignored. It was due to a momentary loss of contact between electrode and scalp giving a false voltage reading. Apart from this it will be seen that resistances vary in an almost random manner from below 200 ohms to above 600 ohms not merely from patient to patient but through almost as wide a range for individual patients on different occasions.

With the first group of instruments with a constant voltage, the joules will actually exceed or fall short of the supposed value in inverse proportion to the ratio between the actual resistance and the assumed value. For example if the assumed resistance is 300 ohms and the actual resistance is 200 ohms, then settings that claim to deliver 20 joules will actually give 30 joules while if the true resistance is 600 ohms the same setting will only deliver 10 joules.

With the second group of instruments using a capacitor the number of joules stored can be calculated from the voltage and the capacitance. In the

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TABLE

Case No.	Age	Consecutive resistances. Highest in series double underlined	Average
C.1	36	367.265.200.227.258.258.245.212.216.228.217.230.275.	245
A.12	67	272.282.333.266.256.250.262.282.243.255.293.361.413.	290
C.2	72	386.213.194.357.282.341.291.412.272.251.269.	297
B.2	72	332.219.336.321.325.290.	304
A.5	65	398.237.376.341.296.301.279.290.268.286.	307
B.3	77	382.309.266.	319
A.8	37	293.291.308.253.434.352.	322
B.10	48	540.246.326.302.276.291.318.	328
D.2	62	404.229.356.362.368.284.308.304.405.312.309.	331
D.18	75	560.317.253.315.302.382.393.360.291.346.356.336.347.	350
D.15	46	667.364.386.341.312.323.327.349.313.325.302.341.277.347.337.401.362.	357
B.14	66	229.360.296.383.353.378.293.403.424.369.356.348.391.445.	359
D.13	43	410.341.414.374.322.	372
B.1	53	465.337.258.379.326.672.496.495.558.248.284.366.347.341.	392
B.11	65	359.390.493.623.326.308.245.283.337.323.408.433.486.303.468.041.423.444.352.504.	396
B.6	81	446.523.361.314.397.	408
B.9	31	488.528.399.1360.466.539.426.380.392.326.330.311.320.292.360.293.272.318.	433
A.7	48	396.811.534.514.407.656.468.532.596.486.427.	438
A.11	69	236.498.465.361.475.564.638.685.502.443.590.631.517.354.286.	483
D.8	84	425.398.561.502.521.448.558.506.530.	494
D.5	74	470.642.514.	542
A.13	49	571.595.589.447.474.497.516.597.592.545.695.585.	558
D.17	63	1000.453.496.496	611

Measurements are all in ohms.

Average of individual minima	290 ohms.
Average of individual maxima	576 ohms.
Average of all 240 measurements	453 ohms.
Average of individual averages	388 ohms.

Transpsycon instrument the mechanical interruptor is the only controlling device and the joules will be discharged in the form of current pulses the amplitude of which is solely determined by the patient's resistance and the voltage in the capacitor. As the latter falls rapidly to zero the current shows a corresponding diminution.

In the Mecta, Ectron constant-current instrument, and the City University instrument there is an electronic control so that no matter how low the

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resistance of the patient the current cannot exceed a particular value. In the two first mentioned this is always set at 825 milliamperes. In the City University instrument a wide range of current values is available. This enables the current to be set to the minimum value capable of producing a convulsion.

Because of the effect of the skull bone and of the variable skin-contact resistances it has been found possible to produce convulsions with currents below 100 milliamperes under favourable conditions in some patients, while currents exceeding 2000 milliamperes have failed to convulse patients receiving anti-convulsant drugs and having skulls lacking low resistance paths.

Unfortunately there is a widely held view that there is no risk attached to higher dosage, so little variation in instrument setting is possible.

Electro-physiologists are well aware that skin resistance measurements are greatly affected by the conditions of measurement. If measurements are made with a single cell between EEG electrodes readings of 5000 ohms are to be expected while at the other end of the scale enquiries of the American prison service have elicited the information that in the electric chair at 950 volts the resistance falls to 63 ohms.

Electrical effects on tissues

The effects of electricity on tissue varies with the type of electricity and the intensity. Apart from the minute quantities of electricity required to produce a static charge there must be at least two points of contact before current can flow through the body. Where one point of contact is deep to the skin, the smallest current can have dramatic effects, particularly if intracardiac. With ECT however there are two points of contact with skin. Cadaveric measurements showed that though the resistance through soft tissue below the skin is always very low, substantially the same as normal saline, it is the path from the one metal conductor to the other through the coupling material, usually cotton wool and lint soaked in sodium chloride or bicarbonate solution and the epidermis that contributes most of the resistance as measured.

The high resistance of the bone has no effect on the measurement of inter-electrode resistance though it has a very great effect on determining the small part of the electricity that traverses the cranial cavity.

All living cells have a small voltage difference between their interior and their surroundings and the effects of electricity are almost entirely due to the effect on this polarising voltage which is a fraction of a volt. Its actual value is in dispute because the electrode used to measure it inevitably distorts the conditions. Neurophysiologists have long known that when the intensity of a current passed along part of a nerve is increased slowly from zero there is no stimulation but the nerve is 'blocked', no action potentials can pass the part of the nerve affected. When the current is cut off, the nerve gradually returns to normal if the current intensity and the time of flow are small. However with high currents and prolonged flow there is no such recovery. This is because the electrolytic action has caused ions to migrate and alter the cell chemistry.

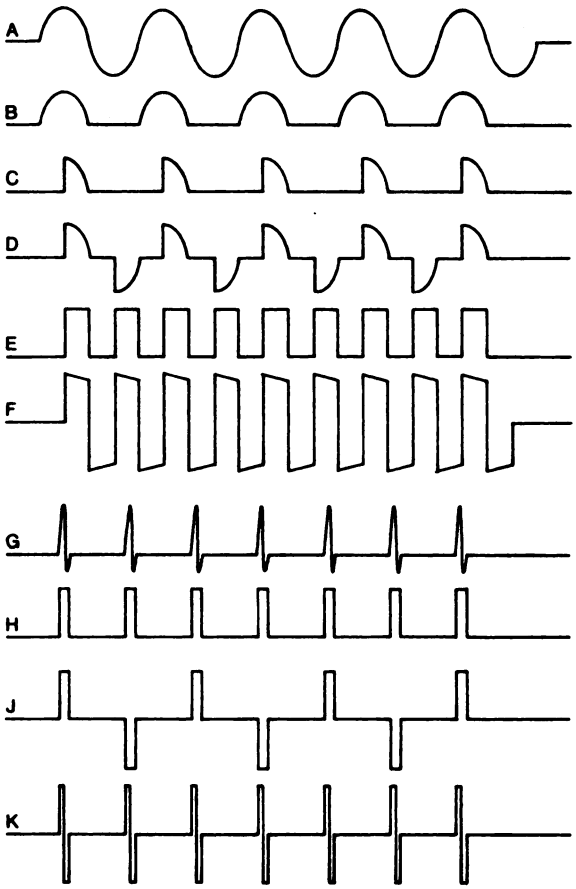


FIG 1.—Stimulus waveforms. (A) Unmodified sinusoid. (B) half-wave rectified sinusoid. (C) half-wave rectified sinusoid with SCR triggering. (D) full-wave sinusoid with SCR triggering. (E) monophasic square waves from mechanical interrupter. (F) diphasic square waves from mechanical interrupter. (G) ultrashort inductive pulses. (H) unidirectional short square waves with long intervals. (J) short square waves in alternate directions with long intervals. (K) short diphasic square waves with long intervals.

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To obtain stimulation instead of inhibition there has to be a rapid change in the current passing. Galvani employed a charged Leyden jar for his classic work (Galvani, 1791) and this provided a sudden surge of current that rapidly decayed to zero. Modern physiologists employ a single 'square wave' pulse that rises rapidly to a level that is maintained for a short period and then either returns to zero or is followed by a similar pulse flowing in the opposite direction. (See Fig 1, H and K).

Where a single pulse occurs the response from a motor nerve results in a single muscle twitch. With repeated such pulses a tetanic contraction is produced. This is true when the interval between pulses is measured in milliseconds. If however a high frequency alternating current passes through the tissues there is no muscular contraction. This is because the current reverses direction so rapidly that no migration of ions occurs. What does happen is that the temperature rises slowly and this is what happens in medical diathermy.

Nerve cells have a refractory phase following a stimulus. Current flowing during this period is wasted so far as stimulation is concerned but it does have electrolytic effects. The optimum pulse duration is from 1.0 to 1.5 milliseconds. Under ECT conditions the electrolytic action is mainly concentrated at the skin surface as was shown in cadaveric measurements.

Types of pulses

Transformer type instruments produce waveforms A, B, C, D (Fig 1) the pulse rate being determined by the mains frequency. The Transpsycon instrument produces waveform E when switched to '1 phase' and waveform F when switched to '2 phase'. There are some Ectron instruments that provide G waveform pulses lasting only 0.3 milliseconds which do not maintain the current level for any significant period. The City University instrument can produce waveforms H, J, or K but H has become standard for routine use. The frequency and the duration of the pulses are capable of variation but are normally 100 pulses per second of 1.0 milliseconds.

It will be seen that with waveforms A or F current is flowing for virtually 100 per cent of the time. With B, D, or E waveforms current is flowing for 50 per cent of the time. In C waveform current flows for 25 per cent of the time. In H waveform the current flows for only 10 per cent of the time at 100 pulses per second but even less at lower pulse rates. For a given peak value of the current flowing, the conventional milliammeter would record currents that are much lower. A would read 71 per cent, B 35 per cent, C 17 per cent, D 35 per cent, E 50 per cent, F 100 per cent, and H 10 per cent or less.

Pulse pattern

With the constant voltage instruments the pulses are all of equal amplitude and there is usually a timer to control the number of pulses. The same is true of the Ectron constant current instrument. In early instruments the so-called glissando device was provided giving increasing voltage in the early part of the shock. This was introduced to reduce the strong muscular contractions when no anaesthetic or relaxant was used. It is obsolete (Fig 2, A).

With the Transpsycon because of the use of a capacitor with no current control, the pulses diminish in amplitude and will fall to zero if the button is held down long enough. In fact the duration is between one and two seconds (Fig 2, B). With the earlier City University instruments the pulses were kept to a constant amplitude at the beginning but then followed the same pattern as the Transpsycon. If the current was high the limitation affected very few pulses but with low currents there was limitation almost throughout (Fig 2, C).

The total number of pulses thus varied from about 100 to 1000 or more depending on the size of the capacitor and the current setting. It was illogical to give such widely differing numbers of pulses so further modifications were made to the City University instrument so that the current control applied throughout the shock and the number of pulses could be selected. By the use of this facility it will be possible to give shocks composed of a selected number of

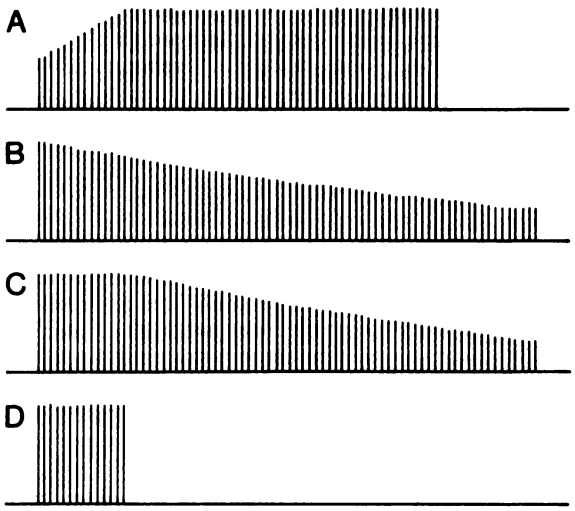


FIG 2.—Pulse patterns. (A) Glissando technique. (B) Capacitor discharge without current control. (C) Capacitor discharge with current limitation. (D) Constant-current pulses of controlled number.

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pulses each of a known peak current value quite irrespective of the variations in resistance (Fig 2, D).

Factors that influence the production of a convulsion

It is necessary first to decide the criteria for diagnosing a convulsion. It has been found that the clinical manifestations have varied considerably with the different types of shock. As soon as the current begins to flow there is a tonic stage. This has been thought to be due to direct stimulation of the muscles. It is however attributable to the stimulation of the motor cortex directly or indirectly. When the electrodes are placed unilaterally on frontal eminence and mastoid it is found that both calf muscles contract equally and synchronously. The strong stimulation of the motor cortex on one side presumably also involves the contralateral motor cortex through the association fibres.

The strength and duration of the tonic stage varies, being most intense and most prolonged with waveform E (Fig 1). With waveform H and 100 pulses per second the tonic stage is less intense and shorter, but if the pulse rate is reduced it is found that the tonic stage becomes so slight that doubt may arise whether a shock has been delivered. It was for this reason that 100 pulses per second were retained as the standard. It was recently reported that ECT had caused rupture of the spleen: as this was presumably due to the tonic stage it was suggested that the risk of such complication would be less if lower pulse frequencies were used (Gordon, 1980). These observations are impossible to quantify as there is no simple method of measuring the tonic contraction of all the muscles of the body and the depth of anaesthesia and the concentration of relaxant at the moment must modify the reactions.

A series of observations have recently been made on the time interval between the start of the shock and the first clonic contractions. This has varied from 2 to 15 seconds but shows no correlation with the current levels. Throughout the series the duration of the convulsion from the beginning of the shock to the last clonic twitch has been recorded and averages 35 seconds. Times below 5 seconds are regarded as failures to convulse. Maletzky's work suggests that the total convulsion time must reach more than 210 seconds to be effective but this does not appear to have been confirmed (Maletzky, 1978, and personal communication).

There are so many permutations and combinations of electrode placements, electrical factors, clinical diagnoses and assessments of degree of depression that statistical analysis of their significance is impossible. The present paper is restricted to showing how the risk of irreversible change in the brain can be kept to the minimum while producing convulsions.

Though convulsions can be produced with a wide selection of electrode positions there is one factor that must be realised. Because most of the electricity passes directly from one electrode to the other through the soft tissues, the proportion that enters the cranial cavity diminishes rapidly as the distance between the electrodes is reduced.

The parts of the skull that are commonly thin are the orbital roof and the squamous temporal. The air-containing para-nasal sinuses and the mastoid air cells are insulators, so with fronto-mastoid unilateral electrodes the electricity that enters the cranial cavity in fact mainly travels from the frontal electrode through the forehead round the frontal sinus to enter the anterior fossa through the anterior part of the orbital plate, leaving the middle fossa through the squamous temporal and then through soft tissues over the temporal bone to the other electrode. Within the cranial cavity the electricity passes in a fairly direct line, but more passes through the cerebro-spinal fluid and the grey matter than through the white matter as myelin is an insulator.

With bi-temporal electrodes the electricity passes through squamous temporal on each side but with bi-parietal electrodes the path will be much the same though a smaller proportion of the electricity will enter the cranial cavity as the inter-electrode distance is less.

It is presumed that owing to the insulating effect of myelin it is the stimulation of the cells of the cortex that triggers a convulsion. With bi-temporal electrodes the current passes through a relatively limited area of cortex on each side, travelling from surface to white matter and vice-versa. With the unilateral technique, the current flow is more or less in the same plane as the cortex and a great deal larger amount of cortex will be stimulated. This probably explains why it is equally effective in producing a convulsion. In the cadaveric experiments the proportion entering the cranial cavity was similar whether the electrodes were unilateral or bilateral so this factor has been ignored in comparing cases.

In those cases where there is a craniotomy opening or a congenital defect in the skull, the situation is quite different. All the electricity entering the skull when one electrode is near such a defect will be concentrated in a relatively small part of the cortex immediately below the defect and this makes the risk of irreversible change much greater. If however the electrodes are placed at approximately equal distances from the defect this risk is eliminated and it is found that similar currents are then needed to those needed for normal skulls.

If standardized doses are administered, as is

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commonly the case, and the patient convulses, it is impossible to tell if the dose was the minimum capable of convulsing or very much more, and there is danger of causing irreversible effects. For this reason a large part of the present project has been devoted to determining the 'threshold current', i.e. the number of milliamperes that will produce a convulsion in a particular patient who will not convulse with lower currents, other conditions being unchanged.

At the Leicester conference it was suggested that X-ray examination of the skull should always be carried out before ECT was instituted. This was received with incredulity as being quite impracticable. On further consideration it is clear that conventional X-ray films will not show the thickness of the orbital roof or the squamous temporal so the recommendation is withdrawn as a routine procedure. However it is certainly highly desirable in any patient who has had any form of cranial surgery (leucotomy?) or skull fracture so that the electrode placement can be selected to avoid the dangerous concentration described above.

An early observation that followed the ability to measure the peak value of the current and the peak value of the volts and consequently enabled the resistance to be calculated, was the superiority of peak current readings over joules, time, millicoulombs or volts in determining the convulsion threshold. The technicalities of the various measurements and their calibration will be published in a technical journal (Gordon, 1982). In the current version of the City University instrument there is a choice of twelve different current values ranging from 80 milliamperes to 1100 milliamperes.

In general it was found that each patient had a clearcut threshold current provided only that the electrodes were adequately separated. There were however a number of cases that sometimes failed to convulse with currents higher than those that had previously been effective. This was traced to the fact that their medication had been changed. The administration of barbiturates greatly raised the convulsion threshold, more so if they were of the prolonged action type used in epilepsy than the short-action thiopentone when this was used instead of methohexitone. Some patients under barbiturates would not convulse with the 1100 milliamperes provided by the City University instrument. They were convulsed by the Transpsycon instrument however at its maximum voltage and it was found that they were receiving currents over 2000 milliamperes. The highest threshold yet found in such a case was in a patient who repeatedly failed to convulse with currents of 2000 milliamperes but did convulse with 2050, 2100, 2160, 2240, 2400 and 2780 milliamperes.

This shock had a duration of about half a second but the current level of over 2½ amperes is ominously close to the 5 amperes used for judicial electrocution in one American state, though of course there the current is passed for five minutes. The desirability of employing only the minimum current needed for convulsing the patient is clear.

The threshold current normally falls in the range 250 to 600 milliamperes but some will convulse regularly with currents less than 100 milliamperes. Some patients therefore are having more than 20 times the necessary current, where no attempt is made to vary the current to match the individual patient. The recommended procedure is to employ a current of about 600 milliamperes for the first shock and then reduce or increase until the threshold is found. With short-acting anaesthetics two shocks only are given even if there is no convulsion.

Where a threshold has been established for a patient but later it is necessary to continue treatment while anti-convulsant drugs are being given, the current level must be increased by about 50 per cent but on limited case material this is only a rough guide.

With the constant voltage instruments the duration of the shock is usually the only variable and the current value is not known. When however a metering device is inserted between the instrument and the patient, it is possible to show that the current varies greatly with supposedly similar shocks. This is due to the variation in the contact between electrode and skin. The suggestion that one shock facilitates a following shock by causing the skin resistance to fall has not been confirmed. A more likely explanation is that when one shock has failed to convulse, the operator presses harder on the electrodes and thus reduces the resistance and causes higher current to flow.

Discussion

The variation of the current required for convulsion is very large but it must be remembered that the amount of electricity that travels through the soft tissues of the scalp has no deleterious effect. It must be assumed that, in the absence of anticonvulsant drugs, the current that traverses the cortex in a particular path and just causes a convulsion, will be very similar in all patients and that the intra-cranial current for the patient with a very high threshold will be much the same as for a patient with a low threshold, all the rest passing extra-cranially.

If therefore the currents are the same through the cortex the number of pulses needed to produce a convulsion should also be the same. With the original form of capacitor discharge instrument there were many more pulses when the current was low than

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when the current was high. For this reason the latest version of the City University instrument will be able to give a selected number of pulses and thus permit a more scientific proof of the hypothesis that the value of the current for the first few pulses is much more significant than the total number of pulses. This will be the subject of future research.

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