A cardiac conduction monitor and probe for intra-operative identification of conduction tissue

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SUMMARY Intraoperative identification of the atrioventricular conduction tissues is essential in some cases of complex congenital heart disease. In using such monitors, difficulties may arise with display and interpretation of the recorded signal, with the maintenance of sinus rhythm, and with the need for a second observer. In this paper we describe the design and construction of a simple monitor which incorporates the following: an atrial pacing module so as to ensure unchanged anterograde conduction to the ventricles and thus avoid changes in PR interval and QRS complex which may occur with surgical manipulation or hypothermia; an audible click which allows the surgeon to confirm capture and an error light which indicates arrhythmias or loss of pacing; an oscilloscope with a 25 mm/s sweep which displays the electrocardiogram and a 650 mm/s sweep for the conduction signal; a variable time width window triggered by the atrial pacing stimulus which is set to occur during the isoelectric PR segment allowing artefact outside this range to be excluded; and a tripolar electrode probe which detects conduction tissue signals whose absolute magnitude is summed to give a single signal. This is also displayed on the oscilloscope and is used to trigger an audible tone and to flash a lamp. The indicator is muted should atrioventricular dissociation or artefact occur during monitoring. The instrument has simplified intraoperative identification of the atrioventricular conduction system and reduced the need for a second observer.

The disposition of specialised atrioventricular conducting tissue in patients with some forms of complex congenital heart disease makes the intra-operative identification of these tissues desirable when contemplating corrective surgery. Though the general disposition of the conducting tissue has now been well documented in most anomalies by morphological studies, the precise location of the atrioventricular bundle and its relation to the crest of septal structures cannot be predicted accurately in each individual case. For such precise localisation intracardiac intraoperative identification of specialised atrioventricular conducting tissue by means of a hand-held probe should allow the surgeon to identify the atrioventricular bundle and its branches. Machines permitting such identification have been described in various forms over the past decade, but most demand the assistance of a second observer, and in this way detract to some extent from their value. In this presentation we report on the design, construction, and use of an intracardiac atrioventricular conduction monitor which does not

require a second observer and which incorporates several other advantageous mechanisms.

Desirable design features

It is well established that the atrioventricular conduction system can be identified by detecting the cardiac electrogram produced as the front of depolarisation moves through the system from the atria to the ventricles (Kaiser *et al.*, 1970).

In considering the design of a machine to monitor this activity, it is first necessary to ensure a constantly conducted supraventricular rhythm. To this end the machine was made to provide atrial pacing during intracardiac mapping (Kaiser *et al.*, 1970). A problem encountered during display of the monitored cardiac electrogram is that the normal trace speed used is 25 mm/s. At this speed it is difficult to study the temporal relation of the cardiac electrogram to the electrocardiogram, the PR interval of each complex being represented by only 6 mm of screen width. However, at a trace speed of 650 mm/s the screen width for the PR interval is lengthened to 160 mm, and this was the speed

chosen for our machine. A major problem with most commercially available detectors is that the surgeon, when manipulating the hand-held probe, unless helped by a second observer, is continually required to alter his field of vision from the heart to an oscilloscope screen. We therefore considered it obligatory to provide an audible signal showing the presence of conducting tissue (Siegel *et al.*, 1974). Finally, we also considered that the hand-held probe should be malleable and should possess a small tip so as to cover as small an area as possible for accurate identification of the specialised tissue.

The machinery to be described was developed in the Medical Electronics Department, Brompton Hospital, and the costing for materials was £980.

Electrode probe

The electrode probe (Fig. 1, 2) is constructed from a stainless steel upper handle and a lower malleable section made of PVC. The tip is made of perspex and on to this are set four silver electrodes 0.5 mm in diameter. A tripolar electrode arrangement has been chosen to eliminate the problem of mis-orientation. The three measuring electrodes are arranged in the form of an equilateral triangle with a space of 1 mm between each. With this arrangement a cardiac electrogram will always be detected on at least two pairs of electrodes if the probe overlies conducting tissue. A fourth electrode incorporated in the probe tip is used as a reference for the input amplifiers, reducing artefact and interference.

Electronics unit

The electronics unit (Fig. 3, 4) consists of 5 main sections: (1) the oscilloscope; (2) the pacemaker

Fig. 1 Malleable tip intracardiac probe dimensions: 17.5 cm; length of malleable probe: 7 cm.

Fig. 2 Tip of probe. Note quadripolar electrode configurations. Fourth probe is for reference. The three cardiac electrogram probes are in an equalateral triangle 2 mm apart.

module; (3) the cardiac electrogram module; (4) the electrocardiogram module; and (5) the timing module.

(1) OSCILLOSCOPE

The oscilloscope is of the long persistence type and it has two operating modes. A slow, non-synchronised mode sweeps at 25 mm/s for display of the electrocardiogram before mapping, while a fast 650 mm/s sweep, pacemaker synchronised, is used for mapping. In the latter mode the oscilloscope displays information occurring in the 250 milliseconds post-pacing pulse.

There are 3 traces. The upper trace is used for display of a surface electrocardiogram. The middle trace is in the form of a broken bar of variable width (timing module), the use of which will be explained below, and the lower trace displays the cardiac electrogram signal.

(2) PACEMAKER MODULE

A constant voltage pacemaker with an output pulse width of 2 milliseconds and an amplitude adjustable from 1 to 9 volts is incorporated in the unit. The rate is continuously variable from 60 to 300 beats per minute. Output is available from a socket on the front panel. The output circuit is electrically isolated to provide patient safety. To help identify capture by pacing, a small red light on the front panel flashes with each pacing pulse coincidental with an audible click. By observation, it can be noted whether the heart is contracting synchronously with the click. Electrical signals are also sent to the oscilloscope to trigger each sweep. Activation of the pacemaker automatically switches on the oscilloscope in a fast synchronised mode of 650 mm/s.

(3) CARDIAC ELECTROGRAM MODULE

The cardiac electrogram signals from the electrode probe are fed to an amplifier via a socket on the front panel. The module contains three separate amplifiers, one for each electrode pair, and the amplifiers employ optical isolation for patient safety. Signals are fed to an absolute circuit which converts negative signals to positive and the outputs from the three circuits are then summed to provide a combined signal. This overcomes the situation where the signals from the three input amplifiers might sum to zero. The amplifiers have a frequency response of 40 to 500 Hz and the gain is adjustable with a control on the front panel over a ratio of 10:1. At a minimum gain a 1 millivolt signal across any electrode pair will result in a 1 cm deflection on the screen. A small light at the top of the module glows if the amplitude of the signal is sufficient to result in a deflection of 1 cm on the screen, and the same pulse that activates the light is also fed to the timing module to sound an audio-tone giving the operator evidence of the presence of specialised conducting tissue.

(4) ELECTROCARDIOGRAM MODULE

The module receives a high level electrocardiographic signal from a cardioscope or theatre monitoring equipment. This alleviates the need for an additional set of patient leads. The gain can be adjusted by means of a front panel control and a small lamp on the front will flash with each R wave. A rate meter is incorporated in this module which is digitally displayed and is useful for determining the rate at which to start atrial pacing. The output from this module is fed to the top trace on the oscilloscope and R wave pulse is fed to the timing module.

(5) TIMING MODULE

This generates a timing period or window between

the pacing pulse and the R wave which can be adjusted in length, both from its start position, that is time from pacing pulse, and its duration. If a cardiac electrogram pulse is received in the window space an audible tone sounds. This facility allows the operator to set the specific period in which the equipment will indicate the presence of a cardiac electrogram signal and does not indicate artefacts detected outside the time window width.

This module also processes pulses fed from the pacemaker and electrocardiogram module as a check for conducted rhythm. If the pacing capture is lost or heart block occurs it will be detected and indicated by an arrhythmia light on the front panel. When this light is on the audible indication of the cardiac electrogram is muted. The arrhythmia light will become extinguished after five beats when error ceases to exist.

All these modules are housed in one cabinet, 50 × 31 × 24 cm (Fig. 3 and 4). Outputs are provided for the recordings of all signals on to a tape recorder or photographic paper for later study.

Preparation of heart for mapping

Intraoperative identification of the atrioventricular conducting tissues in the open heart when on cardiopulmonary bypass must inevitably have potential risk of air embolism, because it is necessary to allow the heart to beat with the atrioventricular chambers open to the air. It is desirable to monitor the conducting tissue at normothermia. Therefore, after extracorporeal circulation has been instituted by means of ascending aortic cannulation and superior and inferior caval cannulae, on establishing full cardiopulmonary bypass the cavae are snared and the aorta is cross-clamped. A perfusion cannula fed from the side arm of the main aortic perfusion line is then inserted into the aortic root. This allows the aortic root to be perfused, maintains

Fig. 3 Circuit diagram for cardiac conduction monitor. CCT, circuit; Amp, amplifier; CH, channel.

Fig. 4 The cardiac conduction monitor, together with oscilloscope, housed in a single cabinet with all switches and calibration knobs on the front panel. Dimensions of cabinet: 50 × 31 × 24 cm.

competence of the aortic valve, and allows coronary perfusion. The heart will then contract normally, even when the cardiac chambers are open.

Artificial pacing of the heart facilitates mapping, thus a pair of pacing electrodes are attached 4 mm apart to the right atrial appendage. This configuration of electrodes has been found preferable to attaching a single active electrode to the atrium and the indifferent electrode to the body tissues.

Fig. 5 Trace from ultraviolet write-out. The surface electrocardiogram (ECG) showing pacing spike and r wave. A cardiac electrogram (CEG) is a summation of electrode probe a, b, and c. The His spike is well seen on the CEG trace. Calibration 0.1 seconds and 1 millivolt.

Operation

The surface electrocardiogram is connected from a cardioscope to the electrocardiogram module. The heart rate is noted, atrial pacing wires are attached to the patient, and the pacemaker is set to a rate of 10 beats per minute greater than its intrinsic rate. The pacemaker is switched on and capture is achieved by adjusting the rate and voltage controls, at which point the arrhythmia light will extinguish. The oscilloscope will now display the PR interval and the sweep will be 650 mm/s. The time window is set to the required position, the electrode probe is connected, and by manipulating the electrode probe over the surface of the endocardium the operator can conduct intracardiac mapping (Fig. 5).

Examples of use

Over the past year the monitor has been used in 29 patients with congenital heart disease (Tables 1 and 2). In 3 with complex congenital heart disease accurate identification of the non-branching bundle proved an invaluable aid to corrective surgery

Table 1 Identification of atrioventricular specialised conducting tissue: on atrial aspect of annulus

Type of congenital heart disease	No.	Positive	Negative
Atrial septal defect (secundum)	4	4	0
Partial atrioventricular canal defect	6	5	1
Complete atrioventricular canal defect	3	3	0
Tetralogy of Fallot	6	5	1
Ventricular septal defect	7	5	2
Total	26	22	4

Fig. 6 Identification of non-branching bundle in (a) congenitally corrected transposition; (b) congenitally corrected transposition with situs inversus; and (c) univentricular heart of left ventricular type with double inlet and left-sided rudimentary chamber. Conductive tissue positive—⊕.

which was performed without damage to the specialised conducting tissues. These were (i) congenitally corrected transposition (Fig. 6a), (ii) congenitally corrected transposition with situs inversus (Fig. 6b), and (iii) univentricular heart of left ventricular type with double inlet and a left-sided rudimentary chamber (Fig. 6c).

Table 2 Identification of atrioventricular specialised conducting tissue: on ventricular aspect of annulus

Type of congenital heart disease	No.	Non-branching bundle	LBB	RBB	Negative
Ventricular septal defect	7		1	5	1
Tetralogy of Fallot	6		2	4	0
Congenitally corrected transposition in situs solitus	1	1			
Congenitally corrected transposition in situs inversus	1	1			
Univentricular heart (LV type) with double inlet and left-sided rudimentary chamber	1	1			

LBB, left bundle-branch; RBB, right bundle-branch.

Discussion

The pioneering work of Stuckey *et al.* (1960), Kaiser *et al.* (1970), and Siegel and his colleagues (1974) has been drawn upon considerably during the design and preparation of this apparatus. We believe that the completed unit has many advantages

over other available designs and machines.

A bipolar electrode system could result in no detection of a cardiac electrogram even when the probe is situated over the conducting tissue, for it is possible for the probe to be so orientated with respect to the advancing front of the depolarisation that a zero potential difference could be present across the electrodes (Siegel *et al.*, 1974; Schatz *et al.*, 1978).

The unit employs electronic circuits to take the absolute value of the signals from each electrode, and then perform a summation. When using this method the possibility of signal cancellation is avoided. The time window configuration displayed on the oscilloscope is similar to that of Siegel *et al.* (1974) and other workers. However, mere use of the time window does not prevent false positive indication occurring in the event of the development of an arrhythmia. In our experience, arrhythmias frequently develop during mapping because of a loss of pacemaker capture, and, as have others, we have noted that the pressure of the electrode probe on the conducting tissue can itself cause temporary atrioventricular dissociation (Schatz *et al.*, 1978). Because of this, we have incorporated circuits into our unit which continuously monitor the pacemaker pulse and the 'R' wave of the electrocardiogram. If an 'R' wave is not detected within a preset time, an arrhythmia lamp is illuminated and the audible bleep, which hitherto had indicated the presence of conducting tissue, is inhibited, thus preventing the recording of false positive signals.

We believe the major advantage of this unit is its simplicity of use for the operating surgeon. It combines, in one instrument, various facilities which in other instruments are separated, in particular, the built-in display oscilloscope with the pace-maker-synchronised time base and the pacing arrhythmia detection circuit. The unit is self contained and requires no additional equipment, facilitating its use at short notice.

It has now been used in 29 patients, being manipulated by the surgeon alone, and has provided identification of the precise localisation of the atrioventricular conduction tissues, whatever the complexity of the malformation (Fig. 6).

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