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Use of a 64 Channel Computerized Cardiac Mapping System in Arrhythmia Surgery

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A multipoint and computerized intraoperative mapping system has been known to be of value in improving the results of surgery for cardiac arrhythmia. It shows great potential as a new tool in the surgical intervention of the more common and lethal types of supraventricular tachyarrhythmias such as atrial flutter and atrial fibrillation. In addition, it also enhances the ability of the investigators to map and ablate the sometimes fleeting automatic atrial tachycardia. The authors developed a 64 channel computerized cardiac mapping system using a microcomputer (Macintosh IIx) and this has been used for basic research in cardiac electrophysiology as well as in arrhythmia surgery. In this system, bipolar electrograms are obtained from 64 different cardiac sites simultaneously at a sampling rate of 1 Ksample/sec and with a continuous and total data storage of up to 30 seconds. When the reference electrode is selected, delay time from the reference point is displayed on a two dimensional diagram of the heart. This system was used in one patient who underwent a surgical ablation of a ventricular tachycardia in whom we observed a ventricular activation sequence involving a variety of rhythms over several minutes. The system design permits easy expansion to a simultaneous sampling from 256 sites. This 64-channel mapping appeared to have the potential to be of great help in our understanding of cardiac arrhythmia as well as in its diagnosis and surgical treatment.

Key Words: Cardiac arrhythmia, mapping, epicardial, electrophysiology

Electrical activation of cardiac tissue has been studied since the early 20th century in order to understand the mechanism of cardiac arrhythmias. Lewis and associates (1914) studied atrial flutter and fibrillation to understand it's mechanism by measuring electrical propagation using a number of electrodes attached to the atrial epicardium of the canine heart. They demonstrated a possible re-entry circuit at the right and left atrium as one mechanism of atrial flutter. Since then, many investigators have studied the electrical propagation of various cardiac arrhythmias (Puech *et al.* 1953; Goodman *et al.* 1971). Local activation was determined on a point by point basis with a roving, hand-held electrode. The difference in activation times was recorded by this electrode. An improved fixed multipoint electrode was introduced in the 1970s. This new system has been used for preoperative and intraoperative mapping in patients with simple cardiac arrhythmia such as Wolff-Parkinson-White syndrome. However, several limitations

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have been noted over the years as progressively more complex cases presented for surgery (Cox, 1987).

The development of an intraoperative computerized mapping system began in 1977 (Ideker *et al.* 1979; Cox, 1987). The original system made it possible to display local epicardial activation times recorded from a sock electrode and to draw isochronous lines manually. Since then, several investigators (Boineau *et al.* 1978; Allessie *et al.* 1984; Witkowski *et al.* 1984) have developed computerized cardiac mapping systems. These systems made it possible to chart the electrical activation sequence of the heart during various cardiac tachyarrhythmias during surgery (Kramer *et al.* 1984; Cox, 1985; Chang *et al.* 1990). Recently, as personal computers became more sophisticated, it became possible to use a microcomputer for cardiac mapping on a multichannel basis. In this study, we developed a 64 channel computerized cardiac mapping system using a personal computer. We have applied this system to the patient for surgical ablation of cardiac arrhythmia.

MATERIALS AND METHODS

Hardware system

The 64-channel cardiac mapping system is composed of a signal input, a personal computer and data processing software. The system receives the signals from multichannel electrodes which are attached on the surface of the heart. These signals are preprocessed at the signal input; the computer then calculates the activation time. The computer used for this system was a Macintosh personal computer (Model IIx, clock speed: 25 MHz) with 16 MB RAM. We selected a Macintosh computer because it had excellent graphic display capacity (Rose *et al.* 1985).

Signal input: The electrical propagation signals of the heart which come from the electrodes are from a few mV to several tens of mV's. These were amplified above the fixed range by preprocessing. The noise caused by the cable and the power were then eliminated. Figure 1 demonstrates a block diagram of the preprocessing in the signal input. At first, the electrode input signals were amplified. In order to protect the patient's heart, the signal acquisition and processing portion were separated. The transformer was isolated. The first order amplified signals were amplified to several Volts amplitude in the main amplifying unit. In these amplified signals, the 60 Hz power supply interferences were eliminated by notch filter which did not influence cardiac electrograms. In order to reject the high frequency noise component which was added during acquisition of the electrical signal, a bandstop filter using switched capacitor filter (SCF) was used. The cutoff frequency selection included 300, 600, 2400, 4800 Hz as se-

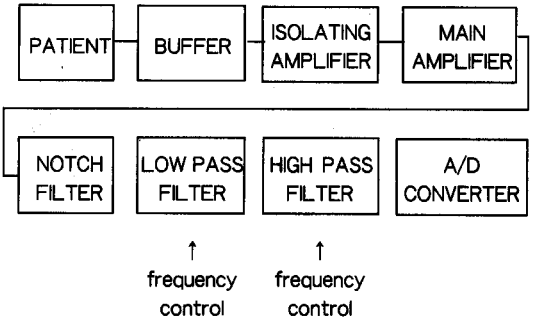

Fig. 1. *Block diagram of the pre-processing.*

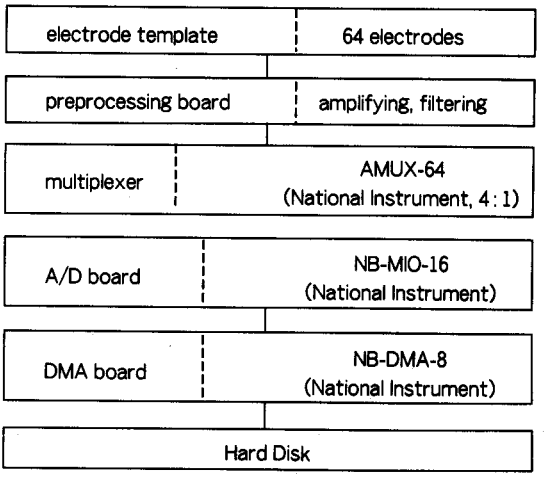

Fig. 2. *Hardware construction.*

lected by the control signal. Furthermore, in order to reject the direct current (DC) and low frequency component, a high pass filter with SCF was used. The cutoff frequency ratings of this high pass filter included 19, 38, 67.5 or 150 Hz. Finally, the amplifying level was controllable at 0.5, 1, 2, 4 times according to the amplitude of the electrical signal in the gain controller. The final design of this amplifier included a component panel which measured 240 mm × 196 mm long.

The preprocessed 64-channel signals were multiplexed at a ratio of 4:1 (AMUX 64, National Instrument®), and were sampled to 1 KHz per channel in a 12-bit A/D converter (16 channels A/D board; NB-MIO-16, National Instrument®) with a 5 V input level. For the buffering of digitized data, a DMA (direct memory access) board (NB-DMA-8, National Instrument®, DMA transfer rate) was used before storing data to the hard disk.

Data processing software

This system was designed to electronically accumulate simultaneous information from multiple intracardiac locations and to facilitate rapid and accurate analysis of this electrical data. The operating system was Macintosh system version 7.0 and the programming tool for signal analysis was think C version 4.0 (Chernicoff, 1989). Data analysis was performed in several automated steps. The software consisted of input signal control, data display, analysis duration selection, calculation of propagation time delay, and cardiac map framing. The functions of the signal input control included multiplexing of the processed 64-channel signals, control of sampling, control of final gain, and hard disk storage. The first four channels among 64 were displayed on monitor from the hard disk, the electrogram was scanned, and a time window of variable length was chosen to study whatever depolarization sequence was of interest (Fig. 3). When the duration of signal which the researcher was interested in, was decided by a search of the reference signal, the 64-channel signals corresponding to the duration were displayed. The propagation time delay from the reference point to the pulse appearing

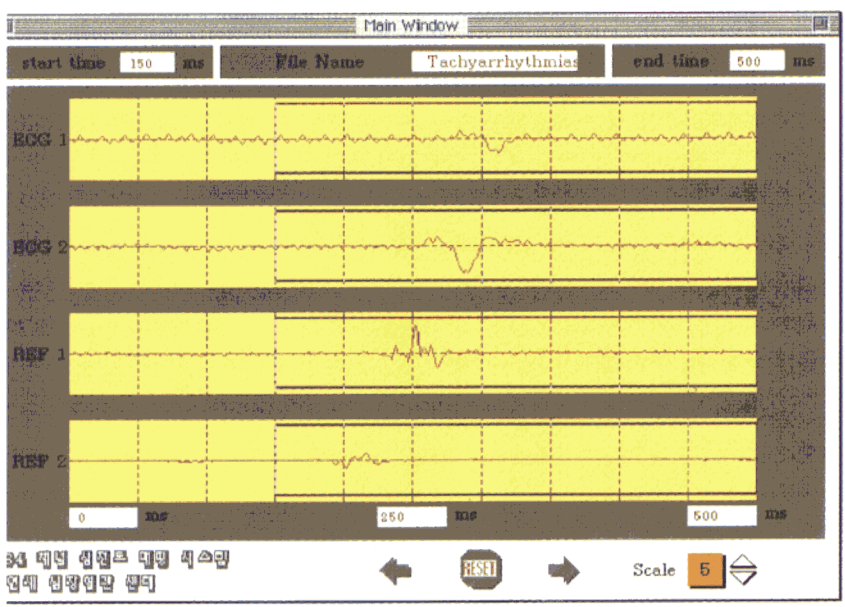

Fig. 3. *Hard copy of the color graphics terminal display of the four digitized bipolar epicardial signals used to select the desired cardiac cycle. The window can be narrowed or enlarged and it can be moved to any portion.*

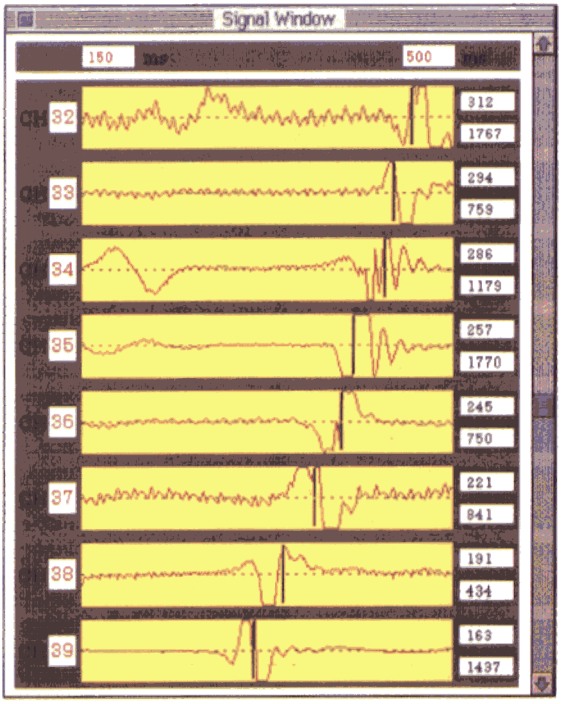

Fig. 4. Hard copy of the color graphics terminal display showing the activation sequence of the 8 bipolar electrodes. The numbers in the right box of each of the electrograms displayed the peak amplitude of the selected points.

point were calculated, and those positions were then displayed. Each electrogram was auto calibrated and displayed along with a computer-chosen activation time based on a peak criterion (Fig. 4). The peak detection method involved obtaining the time of the highest amplitude of bipolar electrograms. Where any deletion in the word count in the raw digital data stream was encountered, data for that 1.0 ms sample was indicated by a visual flag on the display alerting the investigator of the data error. Thus all original electrogram data were visually inspected and all activation assignments adjusted and verified by the investigator. Finally, the time delay from a reference point was displayed using a color coded time sequence on a 2 dimensional diagram of the heart. With the introduction of color coding of time sequence, we could easily identify the electrical activation sequence (Fig. 5, 6).

As an interpolation method for isochronous mapping, we used the distance-weighted least square approximation method (McLain, 1974). We also used an LU-decomposition method in matrix computation (Press *et al.* 1990).

Distance-weighted least square approximation

When we had the n-data points, the value at an arbitrary point (a, b) was computed as follows;

$$P(x, y)=c_{00}+c_{10}x+c_{01}y+c_{20}x^2+c_{11}xy+c_{02}y^2 \quad (1)$$

P(x, y): general polynormial of degree two
Crs: unknown coefficients
x, y: known data point
a, b: unknown data point

We computed the coefficients C_{rs} minimizing Q.

$$Q \quad \sum^{n} (P(x_i,y_i)-z_i)^2 \cdot \omega((x_i-a)^2+(y_i-b)^2) \quad (2)$$

Q: quadratic form

Solving the linear equations $\frac{\partial Q}{\partial C_{rs}} = 0$, to find the unknown coefficient C_{rs}.

By substituting these coefficients into the equation (1), we can find the value of an arbitrary point. The mark ω denotes the weight function,

$$\omega(d^2)=\frac{1}{d^2} \quad (3)$$

The processing speed was, however, very slow; because this method had heavy computational loads, we improved the processing speed by interpolating every two points and setting the uncalculated value to the average of the values of neighbor points.

Multichannel electrodes

Sock electrode: A sock electrode (Cox, 1987) was made for ventricular epicardial mapping. The material used was a flexible cotton mesh that was contoured to fit a normal adult human heart. The wires used for the sock electrode were coated with teflon, and at the tip of wires, silver bead shapes were attached. These were fixed to a button, 1.5 mm apart.

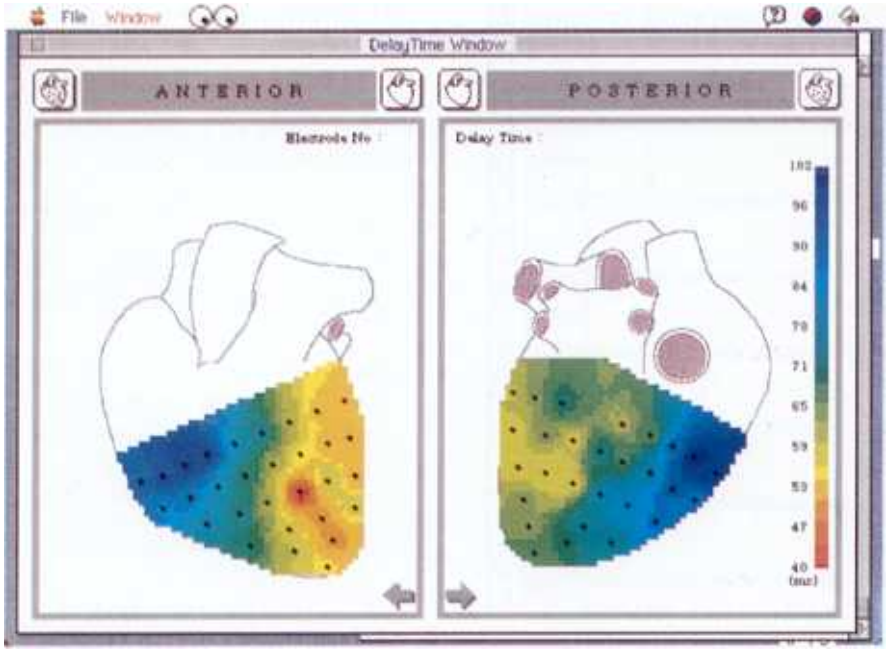

Fig. 5. *Normal sinus activation map of the human ventricular epicardium. The isochronous contours were drawn automatically with color.*

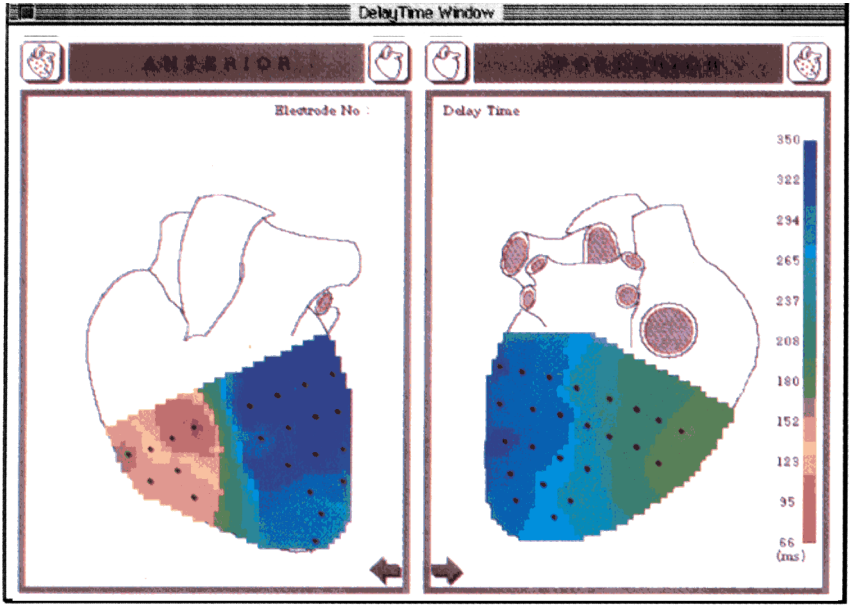

Fig. 6. *Isochronous color map during ventricular tachycardia, 6 years after total correction of tetralogy of Fallot. The slow conduction zone for the tachycardia can be identified at the right ventricular outflow tract.*

Sixty pairs of electrodes were attached to the inner surface of the sock, so the activation sequence of the ventricular epicardium could be obtained from a single beat. The other ends of the 60 pairs of wires were connected into the signal input using a a 25-pin computer connector.

CLINICAL EXPERIMENT AND RESULTS

We tested the 64-channel computerized cardiac mapping system on two patients. One patient, who had presented with a repair of the secundum type atrial septal defect and cryoablation of AV nodal reentrant tachycardia, was studied for normal ventricular activation as a control. The other patient required surgical ablation for ventricular tachycardia.

Under general endotracheal anesthesia, the heart was exposed through a midsternal incision. After systemic heparinization, an arterial perfusion line was inserted through the distal ascending aorta. The apex of the heart was lifted from the pericardial cavity and the ventricle was wrapped with the sock electrode with no difficulty. Positioning of the sock electrode required only minimal cardiac manipulation. During this endeavour, a transient hypotensive episode occurred without any successive myocardial dysfunction. Ventricular activation sequence mapping was performed during sinus rhythm as a control (Fig. 5). For the patient with ventricular tachycardia, the ventricular activation sequence can be studied during ventricular pacing at a cycle length of 400 msec at the right ventricular apex and during ventricular tachycardia (Fig. 6).

Figure 3 demonstrates the main monitor screen showing the reference signal to find the analysis interval. The window of interest for analysis could be narrowed or enlarged and it could be moved to any portion. Figure 4 demonstrates the waveforms of all signals contained in the analysis interval determined. The delay value of the cardiac propagation time is also displayed, and the arrival time is marked with vertical line to make it easy to find unfortunately miscalculated delay value. Figure 5, and 6 are the color epicardial map that shows the calculated cardiac propagation delays corresponding to the positions of the electrodes during normal sinus rhythm and ventricular tachycardia 8 years after total correction of tetralogy of Fallot.

After acquisition of the ventricular activation map, single probe mapping was performed for the patient with ventricular tachycardia. This mapping procedure demonstrated that the patient's ventricular tachycardia was stable and no complication occurred.

DISCUSSION

Electrical activation sequence mapping of the heart is a system which enables the present to study the physiological and pathological electrical activities in the heart. It receives the electrical propagation signal from the heart by electrodes and presents isochronous lines accordingly. There are several available machines with the technology to record electrical activities of the heart. These can be classified into body surface potential mapping and epicardial and/or endocardial mapping technique according to the data acquisition method. The body surface potential mapping uses electrodes attached to the surface of the body, and the epicardial or endocardial mapping receives the signals from the epicardial or endocardial surface of the heart. There are limitations in precise localization of electrical activity for various cardiac arrhythmia with body surface mapping techniques. Recently endocardial or epicardial mapping was used by the majority of electrophysiologists for diagnosis and localization of cardiac arrhythmia. Previous devices for cardiac mapping have depended upon either a single or several exploring electrodes used to record individual electrograms for multiple sites on the epicardial or endocardial surface, sequentially (Puech *et al.* 1953; Goodman *et al.* 1971).

Cardiac mapping techniques have been dramatically improved by the development of si-

multaneous multi-channel data acquisition systems and the application of computer-assisted data analysis (Ideker *et al.* 1979; Allesie *et al.* 1984; Witkowski *et al.* 1984; Kramer *et al.* 1985; Cox *et al.* 1987). They usually use a mini-size expensive computer system with special custom made analysis software. Recently, PC computer technology has been developed with data processing capability that is powerful enough to process up to 256 channels of the data simultaneously. In this study, a 64 channel computerized cardiac mapping system was developed for use with a Macintosh microcomputer. Sixty-four channels of electrical signals from the ventricular surface of the heart were obtained and analysed during arrhythmia surgery. We found that the microcomputer systems enabled the electrical activation mapping to help us to understand the electrical activation sequence involving the normal sinus rhythm and ventricular tachycardia. However, in some cardiac arrhythmia, high resolution cardiac mapping systems with 1 or 2 mm inter-electrode distance may be required. In this situation, a cardiac mapping system of up to 256 channels may be required to understand the electrical propagation of the cardiac tissue. If we need more than 128 channels, calculation time will be taken four times as long as that in our 64 channel system. Therefore, a high speed hardware system for data acquisition as well as a central processing unit will be necessary. For the data acquisition unit, we used a 100 Ksample/sec sampling rate A/D board to obtain 1 Ksample/sec for each channel. If we needed 256-channels mapping system, a minimum 300 Ksamples/sec A/D converter will be necessary. And also, at least, a Pentium®-base PC with more efficient algorithms must the level of the upgrade to process up to 256 channels data. However, in this study, we had not yet installed a math-coprocessor for our cardiac mapping software. If using a math-coprocessor for a floating point calculation, complicated equations for peak detection can be calculated more rapidly.

Regarding software, the peak detection method used in this study was adequate in most normal appearing bipolar waveforms, but during certain abnormal conditions of the myocardium or electrodes, the morphology to these waveforms could be changed markedly, to broad or multiphasic. For this reason, any computer selecting activation point can be overridden, similar to the experience of others (Witkowski *et al.* 1984). These abnormal morphologies usually do not cause difficulties in determining the total activation sequences when these electrograms are carefully compared with closely adjacent recordings. The amplitude of the peak detected or edited by an investigator was displayed at each of the channels and one could move the cursor to other possible peak points accurately with no difficulty. This comparison could be performed by the electrophysiologist without serious problems and no attempt was made to duplicate this decision making process with software. However, when we attempted on-line display mapping systems or simultaneous multichannel potential distribution mapping or activation sequence mapping with unipolar electrodes, it seemed to take a long time to calculate the algorithms. For these, auxiliary systems involving a co-processor or faster 64 bit input-output system will be needed in addition to a powerful Pentium®-based personal computer.

We used Macintosh® computers in our study since 1990 because of the excellent graph display function. Recently an IBM®-based personal computer has been developed and it's speed and capacity for acquisition and analyzing data has almost the same capacity as the Macintosh computer. Moreover, IBM®-based personal computers are less expensive in this country. It appears to us that IBM®-based personal computers have more advantages when it comes to expanding to a 256 channel mapping system and polygraph for medical signal processing.

In this study, we developed a 64-channel computerized cardiac mapping system using a personal computer (Macintosh IIx®) to understand normal and abnormal electrical propagation of the heart. This system has been applied for mapping of the ventricular tachycardia with success. The bipolar electrograms were acquired from 64 cardiac sites of the ventricular epicardium simultaneously at a

sampling rate of 1 Ksamples/sec and stored for up to 30 seconds. When the reference electrogram was selected and reference point was picked up, delay time and a color isochronous map was displayed on a two dimensional diagram of the heart. This study encouraged us to expand to 256 channels for a more detailed mapping study with higher resolution. This system was expected to enable us to study the pathophysiology of various cardiac arrhythmia. Also this system seemed to be very useful for detection and localization of transient cardiac arrhythmia at a low cost comparing to available commercial system.

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