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Virtual Electrode-induced Spiral Reentry in Ventricular Myocardium Perfused in-vitro

Tatsuhiko ARAFUNE,[1] Akira MISHIMA,[2] Ichiro SAKUMA,[1] Hiroshi INADA[2]
Nitaro SHIBATA,[3] Harumichi NAKAGAWA,[4] Masatoshi YAMAZAKI,[4]
Haruo HONJO[5] and Itsuo KODAMA[4]
[1] Bio-Medical Precision Engineering Laboratory, Institute of Environmental Studies, Graduate School of Frontier Sciences, The University of Tokyo, Tokyo 113-8654, Japan
[2] Department of Precision Engineering, Graduate School of Engineering, The University of Tokyo, Tokyo 113-8654, Japan
[3] Tokyo Metropolitan Ohkubo Hospital, Tokyo 160-8488, Japan
[4] Departments of Circulation and [5] Humoral Regulation, Division of Regulation of Organ Function, Research Institute of Environmental Medicine, Nagoya University, Nagoya 464-8601, Japan

Abstract: A new optical mapping system and micro electrodes for recording cardiac excitation propagation from isolated hearts was developed and used in experiments to study the effects of DC defibrillation stimulation induced Virtual Electrode Polarization. Isolated rabbit hearts stained with the voltage-sensitive dye, di-4-ANEPPS, ware illuminated by high luminance bluish-green LED. The emitted fluorescence was cut off lower wavelength than 600 [nm] and captured by high-speed digital video camera (Fastcam40K, Photron). The recorded image was transferred PC and digital image processed. Application of anodal/cathodal point stimulation during resting potential phase resulted in make-excitation derived from virtual electrode and excitation wave front propagated. However, point stimulus during plateu phase induced break-excitation from virtual anode/cathode and some cases of particular coupling interval spiral excitation started from the edge of break-excitation and became reentry. The same mechanism of virtual electrode-induced spiral reentry was observed at point stimulation during ventricular tachycardia (VT). Possible mechanisms of the ventricular fibrillation (VF) starts from defibrillation failure are discussed.

Key words: defibrillation, spiral reentry, optical mapping, virtual electrode

Electrical defibrillation shock is famous treatment against abnormal cardiac pacing. Defibrillation shock makes VT/VF excitation wave fronts change or stop to recover to normal pacing rhythm. But it is pointed that the risk of defibrillation failure brings wave break up and leads to more complex spiral reentry (Brent Mitchell et al, 2002). Past simulation researches using bi-domain model or experimental studies suggest that a point shock induce a complex cell membrane excitation in areas few millimeter distant from the stimulus electrode, called "Virtual Electrode Polarization" (Evimov et al, 2000). It is pointed that virtual electrode phenomenon is the most influential cause of defibrillation failure (Wikswo et al, 1995; Davidenko et al, 1995). However virtual electrode are organized in so minimum regions as well as very short duration that it have been difficult to observe the phenomenon precisely for understanding its formation into spiral reentry. Existing measurement system using photo diode array was low spatial resolution (Evimov et al, 2000). To analyze virtual electrode polarization and wave formation with high spatial and temporal resolution in-vitro, we developed an optical mapping system using high-speed digital video camera recorder and micro-electrodes implanted in a transparent plate.

Materials and Methods

Heart preparation:

Firstly, we stained isolated Japanese white rabbit heart with voltage sensitive dye, Di-4-ANEPPS in the Langendorff-apparatus. BDM was added to the perfusate in order to eliminate mechanical artifacts of signals due to contraction. The hearts ware paced continuously from the base of the right ventricle through a pair of contiguous bipolar electrodes. Cycle length of the basic stimulus was 400 [msec]. Stimulus pulse duration was 2 [msec] and twice the diastolic threshold in intensity (Loew, 1999).

Optical Mapping System:

Measuring cardiac excitation propagation with high spatial and temporal resolution, we chose optical measurement method (Gray RA et al, 1997). Heart was illuminated by high

Reprint requests to: Tatsuhiko ARAFUNE, Bio-Medical Precision Engineering Laboratory, Institute of Environmental Studies, Graduate School of Frontier Sciences, The University of Tokyo, Tokyo 113-8654, Japan.

luminance bluish-green LED (wavelength=500 [nm]). The emitted fluorescent was recorded by high speed digital video camera recorder (Fastcam40K; Photron) passed through a long-path filter (cut-off wavelength=600 [nm]) . Recording speed was 1125 [frames/sec](0.89 [msec/frame]) and spatial resolution of the image was 0.078 – 0.15 [mm/pixel]. Recorded image data was processed by software, and action potential mapping was captured in two-dimensional image. (Fig.1)

Micro Electrode:

To apply point electro-shock with enough current density while optical recording, we developed micro electrodes array implanted in transparent acrylic board. Electrodes consisted of nine plutinum wire (ϕ0.1 [mm]) soldering urethan coating copper wire (ϕ0.04 [mm]). (Fig. 1)

Observation of Basic Virtual Electrode Phenomenon:

Using optical mapping system and transparent microelectrodes array, basic virtual electrode phenomenon was observed. In order to prevent the intramural wave propagation, we produced a subepicardial sheet preparation by endocardial cryoablation.

Make-excitation:

Anodal/cathodal shock (20 [V], 10 [msec] pulse duration) ware applied at resting phase of action potential, and it was observed make-excitation from virtual electrode polarization.

Break-exicitation:

Anodal/cathodal shock (20 [V], 10 [msec] pulse duration) ware applied at plateu phase to repolarization phase, and observed break-excitation started from the end of stimuli. Baseline pacing (S1) was applied with one microelectrode and premature shock (S2) by nearby electrode. Coupling interval (S1-S2) was 200 [msec].

Observation of Virtual electrode from defibrillation shock during ventricular tachycardia:

In response to basic experiment, virtual electrode polarization of defibrillation shock during VT and excitation from virtual electrode were observed. In order to induce sustained VT easily, heart specimen were setup without cryoablation.

VT cycle length was 90 – 100 [msec] and defibrillation stimulation parameter were 20 [V], 10 [msec] pulse duration, 135 [msec] cycle length, and 5 times electro shock from one electrode.

Results and Discussion

Virtual electrode induced make-excitation propagation occurred along the cardiac muscle fiber direction 0.3–3 [mm] distant from the electrode with a current shock applied at resting potential level (Fig. 2). The shape of virtual electrodes ware subject to the anisotropy of myocardium fiber direction.

In the case of shock applied at repolarization phase of baseline pacing action potential, break-excitation came up from hyperpolarized area at the end of shock, and some excitation changed to spiral type excitation at four edges of the virtual electrode polarization (Fig. 3).

The same mechanism of spiral reentry formation was identified at shock applied during VT (Fig. 4). The last shock of five defibrillation shocks applied at plateu phase of VT, and

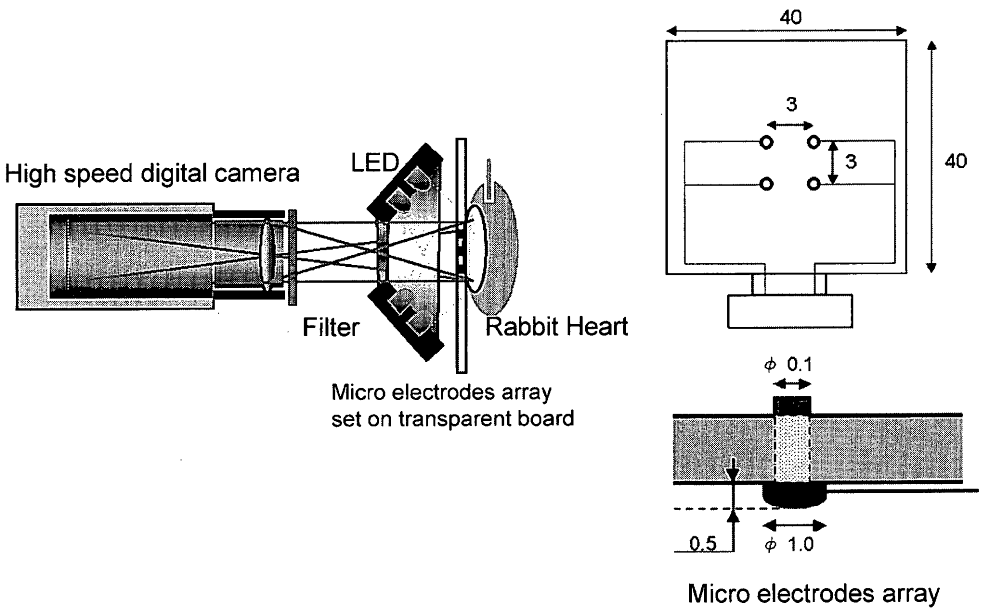

Fig. 1 Optical mapping system using high speed digital video camera and micro electrodes (Pt) array implanted in transparent acrylic board.

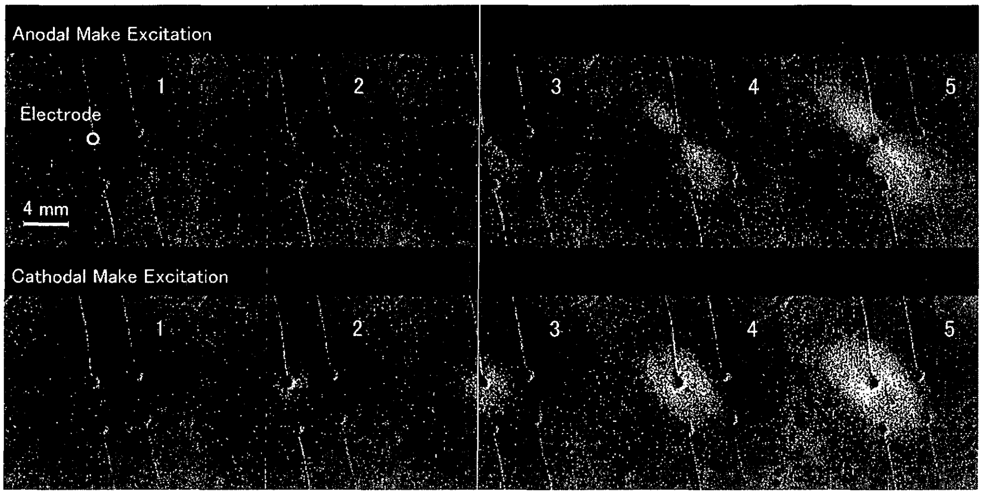

Fig. 2 Virtual electrode induced make excitation image (every 2 [msec]). Stimulation parameter was Anodal/Cathodal shock, 20 [V], 10 [msec] pulse duration. Image No. 1 is shock applied frame. Anodal virtual electrode was formed around stimulation electrodes.

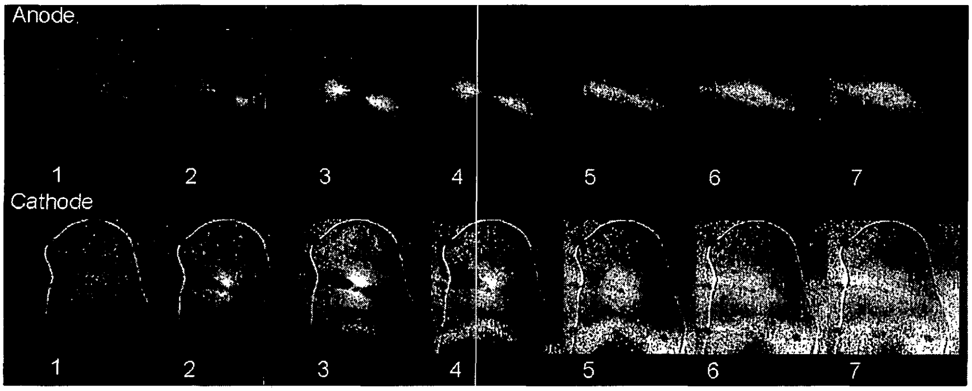

Fig. 3 Virtual electrode induced break excitation image (every 4 [msec]). Schok was applied at plateu phase. Image No.1 is shock applied frame. No. 1 to 4 shows virtual anode formation, and No. 5 to 7 shows break-excitaion.

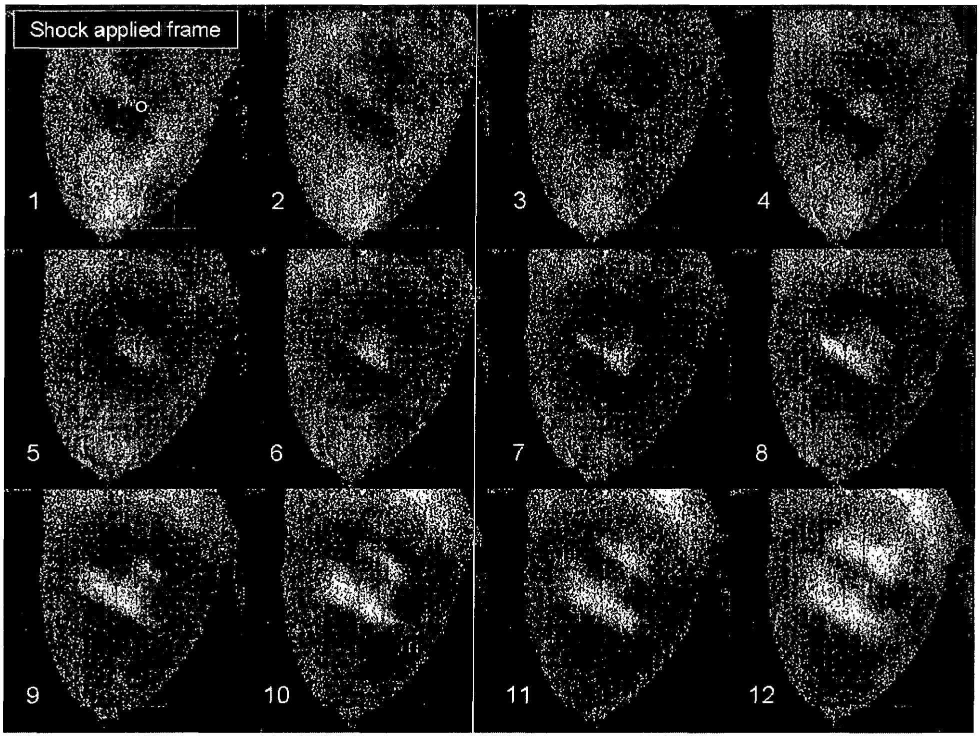

Fig. 4 Virtual electrode formed by point shocks during VT. Image No. 1 was the last shock applied frame (Every 4 [msec]). Image No. 1 to 3 shows virtual anode formation and No. 4 to 8 shows break-excitaion. Then No. 9 image shows spiral exicitation started form the edge of the dog-bone shape break-exicitaion, and re-entry started.

virtual electrode induced break excitation was occurred. Spiral type reentrant excitation wave was started at four edges of break excitation. Then the four spiral type reentry ware under conditions of refractory area of last excitation wave and it changed to polymorphic spiral reentry. It is thought that the way of fatal VF mechanism starts from defibrillation shock failure.

We developed virtual electrode observation system using optical mapping and microelectrodes array on transparent board. Compared with existing system, it accomplished one digit higher spatial and temporal resolution mapping. Using the system, we cleared up that the break excitation that rise from virtual electrode have an important role on the formation of spiral reentry at defibrillation shock.

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