Efficacy and Myocardial Injury With Subcutaneous Implantable Cardioverter Defibrillators
– Computer Simulation of Defibrillation Shock Conduction –

Mahito Noro, MD, PhD; Xin Zhu, PhD; Yoshinari Enomoto, MD; Masako Asami, MD; Rina Ishii, MD; Yasutake Toyoda, MD; Naohiko Sahara, MD; Takahito Takagi, MD; Yuriko Narabayasi, MD; Hikari Hashimoto, MD; Naoshi Ito, MD; Shingo Kujime, MD; Yasuhiro Oikawa; Hiroyuki Tatsunami, BSc; Tsuyoshi Sakai, MD, PhD; Keijirou Nakamura, MD, PhD; Takao Sakata, MD, PhD; Kaoru Sugi, MD, PhD

Background: Subcutaneous implantable cardiac defibrillator (S-ICD) systems have a lower invasiveness than traditional ICD systems, and expand the indications of ICD implantations. The S-ICD standard defibrillation shock output energy, however, is approximately 4 times that of the traditional ICD system. This raises concern about the efficacy of the defibrillation and myocardial injury. In this study, we investigated the defibrillation efficacy and myocardial injury with S-ICD systems based on computer simulations.

Methods and Results: First, computer simulations were performed based on the S-ICD system configurations proposed in a previous study. Furthermore, simulations were performed by placing the lead at the left or right para-sternal margin and the pulse generator in the superior and inferior positions (0–10 cm) of the recommended site. The simulated defibrillation threshold (DFT) for the 4 S-ICD system configurations were 30.1, 41.6, 40.6, and 32.8 J, which were generally similar to the corresponding clinical results of 33.5, 40.4, 40.1, and 34.3 J.

Conclusions: The simulated DFT were generally similar to their clinical counterparts. In the simulation, the S-ICD system had a higher DFT but relatively less severe myocardial injury compared with the traditional ICD system. Further, the lead at the right parasternal margin may correspond to a lower DFT and cause less myocardial injury. (Circ J 2016; 80: 85–92)

Key Words: Computer simulation; Defibrillation threshold; Implantation site; Myocardial injury; Subcutaneous implantable cardioverter defibrillator

Recently, the subcutaneous implantable cardioverter defibrillator (S-ICD) was approved by the US Food and Drug Administration (FDA) and put to clinical use in Europe and the USA. Given that the lead of the S-ICD system indwells in the mediastinum instead of being inserted in the right ventricle as in the traditional transvenous ICD system, the implantation of the S-ICD system will not cause any direct trauma to the heart and veins. In the case of a device infection or lead fracture, the leads of the S-ICD systems can be removed minimally invasively. Experiments based on a swine model also proved that S-ICD shocks cause less myocardial injury than the traditional transvenous ICD system. Also, patients benefit from S-ICD systems because the indications for S-ICD systems may include patients considered infeasible for implantation of the transvenous ICD systems, and patients not requiring pacing.

The standard defibrillation threshold (DFT) with S-ICD systems, however, is 80 J, which is more than 4-fold that of the traditional ICD systems. Based on basic and clinical experiments, ICD shocks with traditional transvenous ICD systems induce myocardial injury, and shocks with a higher output cause more severe myocardial injury. In addition, previous...
Computer Simulation

Finite element modeling of the defibrillation in this study was conducted using the SCIRun software and dataset, an Open Source software project of the SCI Institute’s NIH/NIGMS CIBC Center. In the dataset, a human torso model was built from cardiac-gated magnetic resonance imaging of a healthy, 19-year-old volunteer. The spatial interval between neighboring images was 5 mm, and every image had a dimension of $256 \times 256$. The boundary nodes, surface, volume, and meshes were obtained to construct a geometrical model of the human thorax. Based on the human torso model, 4 models (Figure 1) were used to simulate the potential distribution and spatial voltage gradients during the ICD defibrillation using the SCIRun numerical analysis modules based on a finite element method with a solution to the Laplacian equation. Furthermore, the torso models were piecewise made heterogeneous by setting different electrical conductivities for the different tissues: bowel gas, 0.002; connective tissue, 0.220; liver, 0.150; kidney, 0.070; skeletal muscle, 0.250; fat, 0.050; bone, 0.006; lung, 0.067; blood, 0.700; and myocardium, 0.250 siemens/m. The models were also divided into hexahedral volume meshes and affined automatically in view of the organ structure in SCIRun. Finally, the simulation results were also visualized using the SCIRun visualization modules. In clinical practice, a DFT is defined as the minimum requirement of actual energy (Joules) from an ICD generator for successful defibrillation. In computer simulations, we used a critical mass hypothesis to define the success of the defibrillation with different ICD generator configurations. Based on the critical
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mass hypothesis, the DFT in the simulation was the minimum energy output of the ICD generator with a voltage gradient >5 V/cm for >90% of myocardium.\(^{18,19}\) Furthermore, we also calculated the percentage of myocardium with a voltage gradient >30 V/cm as an index to predict any possible myocardial injury.\(^{18,19}\) DFT was calculated using \(E=\frac{1}{2} \cdot C \cdot V^2\), where \(C=130 \mu F\) and \(V\) is the defibrillation voltage, given that the defibrillation critical mass criterion was reached. The anatomical heart model was manually segmented into the left and right ventricles. In order to determine the defibrillation homogeneity, the DFT and myocardial damage were estimated for the whole ventricular mass, the left ventricle, the right ventricle, respectively. The ventricular septum was separated into 2 right and left parts considering the distance from the endocardial surfaces of the left and right ventricles. In the simulations, the DFT of the whole ventricular mass was the minimum defibrillation energy when 90% of the whole ventricular mass had a spatial voltage difference >5 V/cm, and the DFT of the right or left ventricles was the minimum defibrillation energy when 90% of the right or left ventricular mass had a spatial voltage difference >5 V/cm.\(^{19}\)

**S-ICD Simulation Configurations**

First, we reproduced the conduction of the defibrillation shocks in human beings based on 4 implantation configurations of the S-ICD systems. The 4 configurations were proposed by Bardy et al,\(^1\) and include (Figure 1A) a left lateral pulse generator with an 8-cm coil electrode positioned at the left parasternal margin; (Figure 1B) a left pectoral pulse generator with a left parasternal 4-cm coil electrode positioned at the inferior sternum; (Figure 1C) a left pectoral pulse generator with an 8-cm coil electrode curving from the left inferior parasternal line across to the inferior margin of the left sixth rib; and (Figure 1D) a left lateral pulse generator with a left parasternal 5-cm\(^2\) oval disk. We calculated the DFT from the simulation results for each configuration, and compared the simulated DFT with published data\(^1\) to validate the computer simulation. In addition, the simulated myocardial injury was also estimated from the simulation results.

Second, a left lateral pulse generator with an 8-cm coil lead placed at the left parasternal margin was recommended by Bardy et al, and has been a clinical standard for the implantation of S-ICD systems. We proposed a similar implantation method but with the 8-cm coil lead positioned at the right parasternal margin. In view of the DFT and myocardial injury, we compared the simulation results between these 2 implantation configurations.

Third, for the configurations with 8-cm coil leads placed at the left or right parasternal margin, an additional computer simulation was performed when the S-ICD generator was implanted in positions 1 cm, 2 cm, 3 cm, and 10 cm inferior, and 1 cm, 2 cm, and 3 cm superior to the traditional left lateral location, that is, the implantation sites of the pulse generator were located around and inferior to the diaphragm. The corresponding simulated DFT and myocardial injury were calculated and compared between the systems with the coil leads positioned at the left or right parasternal margin.

### Results

Figure 1 illustrates the electric field lines simulated based on the 4 proposed S-ICD configurations in the published data.\(^1\) For configuration A (Figure 1A), the electric field lines were divided into anterior and posterior streams from the pulse generator (Figures 1E–G). Then, both streams travelled in upward, transverse, and downward directions, avoiding the lungs. The upward stream in the posterior region traveled around the superior region of the back, passed through the right anterior chest, and ended at the upper side of the S-ICD coil lead (Figure 1E). The transverse stream in the posterior region traveled from the middle of the back to the middle of the S-ICD coil lead (b, Figure 1G). The downward stream in the posterior region traveled from the diaphragm posterior around the bottom of the heart (Figures 1F,G) or travelled around the inferior region of the back (c, Figure 1G), ending inferior to the S-ICD coil lead. As for the conduction in the front, the upward stream travelled around the upper precordial chest and right precordial chest, ending superior to the S-ICD coil lead. The transverse stream travelled from the front of the mediastinum, and the downward stream travelled around the abdomen and then inferior from the right anterior chest. Both ended at the middle and inferior to the S-ICD coil lead. For configuration B (Figure 1B), the electric field lines were divided into 2 streams: 1 travelled across the precordial chest and ended superior to the coil lead, and the other travelled downward to the back of the abdomen, then returned to the chest, and finally ended inferior to the S-ICD coil lead. The simulation based on configuration C had a similar electrical conduction pattern to that of configuration B. The electric field lines in the right lateral region had a higher density in configuration C than configuration B (Figure 1H).

The simulation based on configuration D also had a similar electrical conduction pattern as that of configuration A. The electric field lines in the right lateral region had a lower density in configuration A than configuration D (Figures 1G,M). The main difference in configurations A,D and B,C was that there were more electric field lines passing through the heart from the anterior to the posterior and inferior region of the heart in configurations A,D (Figure 1F, x and y positions).

The average DFT in the clinical trial\(^1\) and simulated DFT were 32.5 J vs. 30.1 J for configuration A; 40.4 J vs. 41.6 J for configuration B; 40.1 J vs. 40.6 J for configuration C; and 34.3 J vs. 32.8 J for configuration D, respectively. Thus, the clinical and simulated DFT had similar trends and values (Figures 2A,3A).

In the simulation, the clinically recommended configuration A corresponded to the lowest DFT of 30.1 J, and the percentage of myocardial injury was 2.5%, 0%, and 4.0% for the whole ventricular mass, left, and right ventricles, respectively (Figure 2E). In the simulation, the left and right ventricular simulated DFT were 49.2 J vs. 33.7 J and 47.0 J vs. 27.5 J for configurations B and C with a left pectoral pulse generator, respectively. The simulated DFT of the left ventricle was at least 15 J higher than that of the right ventricle. For configurations A and D with a left lateral pulse generator, however, there was a much smaller difference between the left and right ventricular DFT, which were 26.6 J vs. 34.6 J and 29.2 J vs. 34.6 J for configurations A and D, respectively (Figure 3B). Therefore, in the simulations, the ventricular mass vs. defibrillation voltage curves with voltage gradient above the local DFT (5 V/cm) were similar for the whole ventricular mass, left, and right ventricles for configurations A and D (Figures 2A,D).

As for configurations B and C, the right ventricular mass at which the gradient was >5 V/cm was higher than that of the whole ventricular mass and left ventricle (Figures 2B,D). These simulation results showed that the defibrillation current was more likely conducted to the right ventricle than the left ventricle for the left pectoral pulse generator configuration, but was nearly equally conducted to the right and left ventricles for the left lateral pulse generator configuration. Consequently, the myocardial injury in the right ventricle was more
from the S-ICD generator were also divided into anterior and posterior streams and travelled in an upward, transverse, and downward direction, avoiding the lungs. According to the arrays (Figure 4), there was more defibrillation current conducted to the heart via the left anterior chest using the coil lead severe with the left pectoral pulse generator configuration, but was better controlled with the left lateral pulse generator configuration.

When the S-ICD coil lead of configuration A was placed at the left parasternal margin (Figure 4), the electric field lines

Figure 2. Proportions of ventricular mass vs. defibrillation voltage curves (red curve, whole ventricular mass (right ventricle [RV] and left ventricle [LV]); black curve, LV; green curve, RV). Proportions of ventricular mass at which the voltage gradient is above (A–D) the local defibrillation threshold (DFT) and (E–H) the local myocardial injury threshold for the configurations A–D in Figure 1. Red array lines, (A–D) DFT; (E–H) myocardial injury.

Figure 3. (A) Comparison of the simulated and average defibrillation threshold (DFT) of the whole ventricular mass for the 4 configurations of the subcutaneous implantable cardiac defibrillator (S-ICD) systems (Bardy GH, et al1). (B) Simulated DFT for the whole ventricular mass, left ventricle (LV), and right ventricle (RV). (C) Proportions of simulated ventricular mass with myocardial injury for the whole ventricular mass, LV, and RV.
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Figure 4. (B–D,G–I) Simulated electric field lines in the (B,G) frontal, (E,H) left lateral, and (D,I) posterior views for configurations with a coil lead placed at the (A) left and (F) right parasternal margins. (E,J) Locations of myocardium with injury (red) for the 2 configurations, respectively.

Figure 5. (A,B) Proportions of ventricular mass at which the voltage gradient is above the (A) local defibrillation threshold (5V/cm) and (B) myocardial injury thresholds, for simulation of the configuration with a coil lead placed at the right parasternal margin. Red curve, whole ventricular mass (right ventricle [RV] and left ventricle [LV]); black curve, LV; green curve, RV. (C,D) Comparison of the (C) simulated DFTs and (D) proportions of simulated ventricular mass with myocardial injury for the configurations with a coil lead placed at the right and left parasternal margins, respectively.
The main conduction regions of the defibrillation shocks to the heart, surrounded by the lungs and mediastinum, are the part of the diaphragm close to the heart, the posterior diaphragm and its neighboring left ventricle, the part of the diaphragm extending to the abdomen and the neighboring right ventricle, and the mediastinum excluding the lungs and bones with high resistance. It is hypothesized that the defibrillation current in the left ventricle mainly comes from the back of the diaphragm and the posterior mediastinum, and that in the right ventricle comes from the abdominal region of the diaphragm and anterior region of the mediastinum. Therefore, the defibrillation efficacy may be improved if more of the defibrillation current via the back of the diaphragm can be conducted to the left ventricle.

As for the S-ICD systems, in the case of a left pectoral implanted pulse generator (configurations B and C) and a coil lead positioned at the left parasternal margin, the defibrillation current was conducted mainly over the anterior chest and was decreased on the back. In the case of a left lateral implanted pulse generator (configurations A and D), the defibrillation current was approximately equally conducted to the anterior chest and back. The defibrillation shock conduction pattern of the left lateral pulse generator looked like that of the left pectoral pulse generator with a clockwise rotation. The defibrillation shocks were conducted in the upward, transverse, and placed at the left parasternal margin. In the simulation, the DFT for the coil lead placed at the right and left parasternal margins were 25.4 J vs. 30.1 J (DFT of the whole ventricular mass), 29.2 J vs. 26.6 J (DFT of the left ventricle), and 23.4 J vs. 31.8 J (DFT of the right ventricle), respectively. The proportions with myocardial injury were 0.4, 0, and 0.7% for the whole ventricular mass, left, and right ventricles for the coil lead placed at the right parasternal margin when the defibrillation output was the DFT (25.4 J). It was observed that the coil lead positioned at the right parasternal margin may lead to a lower DFT and less myocardial injury (Figure 5). Furthermore, the ventricular mass vs. defibrillation voltage curves were similar for the whole ventricular mass, right, and left ventricles for the coil lead placed at the left or right parasternal margin (Figure 5). The curves for the coil lead placed at the right parasternal margin had steeper gradients (Figure 5B). The coil lead placed at the right parasternal margin may also lead to less severe myocardial injury (Figure 4).

In view of the influence of the S-ICD pulse generator implantation site, for the coil lead positioned at the left parasternal margin, the simulated DFT were 32.8, 31.8, 30.9, 30.1, 29.2, and 29.2 J, and the simulated extent of the proportions of the whole ventricular mass with myocardial injury was 2.7, 2.6, 2.5, 2.5, 2.4, and 2.3% for the implantation sites –3, –2, –1, 0, 1, 2, and 3 cm perpendicularly from the recommended position (Figure 6). For the coil lead positioned at the right parasternal margin, the simulated DFT were 27.5, 26.6, 26.0, 25.4, 25.4, 25.4, and 26.2 J, and the simulated extent of the proportions of the whole ventricular mass with myocardial injury was 0.6, 0.5, 0.4, 0.4, 0.4, 0.4% for the implantation sites –3, –2, –1, 0, 1, 2, and 3 cm perpendicularly from the recommended site. Apparently, low DFT and less myocardial injury may be obtained by implanting the S-ICD pulse generator close to the bottom of the heart. The simulated DFT increased, however, when the S-ICD pulse generator was implanted 10 cm inferior to the normal position.

**Discussion**

The main conduction regions of the defibrillation shocks to the heart, surrounded by the lungs and mediastinum, are the part of the diaphragm close to the heart, the posterior diaphragm and its neighboring left ventricle, the part of the diaphragm extending to the abdomen and the neighboring right ventricle, and the mediastinum excluding the lungs and bones with high resistance. It is hypothesized that the defibrillation current in the left ventricle mainly comes from the back of the diaphragm and the posterior mediastinum, and that in the right ventricle comes from the abdominal region of the diaphragm and anterior region of the mediastinum. Therefore, the defibrillation efficacy may be improved if more of the defibrillation current via the back of the diaphragm can be conducted to the left ventricle.
downward directions with the left lateral pulse generator. The defibrillation current in the transverse direction crossed along the heart. With an increase in the defibrillation current along the back, more of the defibrillation current was conducted to the left ventricle from the diaphragm along the back and posterior region of the mediastinum (Figure 4). This trend was also found in the clinical trials. The difference between the DFT might mainly be attributed to the conduction from the defibrillation current from the back to the left ventricle. In cases of heart failure, however, the pulmonary congestion may reduce the lung’s resistance, increase the defibrillation current from the back of the heart, and finally reduce the clinical DFT even for a configuration with a left pectoral pulse generator. The size of heart may also change the amount of defibrillation current from the mediastinum in the back and anterior chest. Although the simulated DFT of the left pectoral pulse generator tended to be higher than that of the left lateral pulse generator, it may be necessary to study the most feasible implantation site of a pulse generator and coil lead in view of the basic disease and heart size in clinical practice.

In this study, we proposed a configuration with a left lateral pulse generator and a coil lead in the right parasternal margin. This configuration was considered based on the counterpart of automatic external defibrillators with a DC pad placed on the right anterior chest and left lateral side, respectively. Furthermore, the myocardial injury may be significantly reduced because of the mediastinal tissue between the coil lead and right ventricle. In the simulation, the DFT of the right ventricle for a coil lead placed on the right parasternal margin was 8.4 J lower than that for a coil lead placed on the left parasternal margin. This may be because (1) for the coil lead on the left parasternal margin, the right ventricle was more likely defibrillated by the defibrillation current, which was from the back and was weaker because of the longer conduction route; the left ventricle was mainly defibrillated by the defibrillation current along the anterior chest; and (2) for the coil lead positioned on the right parasternal margin, the right ventricle was defibrillated by the defibrillation current from the anterior chest and back, and therefore had a lower DFT. In contrast, the DFT of the left ventricle was 2.6 J higher than that for the coil lead placed at the left parasternal margin. This may be cause the coil lead at the right parasternal margin was a little farther away from the S-ICD pulse generator and therefore the defibrillation current became weaker in the left ventricle compared with the coil lead placed at the left parasternal margin configuration. Nevertheless, the DFT of the entire ventricle for the coil lead placed at the right parasternal margin was 4.7 J lower than that for the coil lead placed at the left parasternal margin. Thus, when an indwelling coil lead is placed at the right parasternal margin, the myocardial injury in the right ventricle and the DFT of the entire ventricle may be reduced without difficulty during the procedure, and may benefit patients with right ventricular myocardial disorders such as arrhythmogenic right ventricular cardiomyopathy.

The coil lead of S-ICD systems is also used for atrial sensing. Inappropriate shocks with S-ICD systems have been reduced using ICD programming such as the recognition of supraventricular tachycardia, and T wave oversensing. The influence of a coil lead placed at the right parasternal margin on the atrial sensing remains unknown and has never been reported. Given that a coil lead placed at the right parasternal margin may reduce the DFT of S-ICD systems, a clinical trial is necessary to study this novel lead configuration.

For the recommended S-ICD configuration involving a left lateral pulse generator and coil lead placed at the left parasternal margin, the implantation site of the coil lead is determined by the puncture site, and therefore we can study only the influence of the left lateral pulse generator implantation site on the defibrillation efficacy. Furthermore, a variation in the position of the left lateral pulse generator may be caused by body posture and respiration, and therefore may change the DFT and amount of myocardial injury. Therefore, we performed computer simulations to study the implantation site variations of pulse generators with relation to the position of the heart.

From the simulation results, the pulse generator placed close or inferior to the bottom of the heart may correspond to lower DFT compared with that placed superior to the heart. This might be related to the reduced upward, but increased transverse and downward, defibrillation current from the pulse generator when the pulse generator was close to the bottom of heart because of the influence of the lungs. When the pulse generator was placed in a position approximately 10 cm inferior to the diaphragm, however, the DFT was greatly increased and the defibrillation efficacy was reduced.

Conclusions

In this study, we performed a computer simulation to investigate the conduction of defibrillation currents in the human body. The simulated DFT were similar to the average DFT in the clinical trials for 4 proposed S-ICD configurations. In addition, the simulation results showed that a novel configuration with a left lateral pulse generator and a coil lead placed at the right parasternal margin may prevent myocardial injury in the right ventricle, and therefore may serve as an alternative selection for S-ICD systems. Furthermore, the defibrillation efficacy may be improved by implanting S-ICD generators at horizontal planes close to the bottom of the heart. The defibrillation efficiency may be reduced if the S-ICD pulse generator is implanted underneath the diaphragm.

Study Limitations

First, in clinical practice, the biphasic defibrillation waveform has been routinely used rather than the monophasic defibrillation waveform. Cardiac ion channels, however, should be considered to explain the lower DFT and less severe myocardial injuries brought about by the biphasic defibrillation waveform. In this simulation, we used only a realistic heterogeneous conductivity torso model to simulate the distribution of defibrillation voltage and its gradient in a human body. Therefore, only the DFT and myocardial injuries using the monophasic defibrillation waveform were simulated in this study. In the future, we expect to develop a diffusion-reaction model considering the cardiac ion channels to simulate the defibrillation efficiency of the biphasic defibrillation waveform.

Second, in the computer simulation, we studied only the influence of the pulse generator implantation sites on the defibrillation efficacy and myocardial injury, but did not discuss the relationship of the size of the body and heart to defibrillation efficacy. This relationship may be related to a subject’s physique and basic diseases. In this study, we performed only a computer simulation based on a heart model and the implantation sites of pulse generators.

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Conflicts of Interest

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