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Technical note

Mechanical compliance of the endocardium

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Abstract

Radio-frequency (RF) ablation is an accepted treatment for cardiac arrhythmias related to abnormal focal cardiac substrate. The penetration depth of the electrode into the endocardium affects lesion size, a critical determinant of success of RF ablation. We measured the relation between the mechanical compliance and the penetration depth of RF ablation catheter electrode at frequently ablated areas of the endocardium and examined the influence of time after death on mechanical properties of the tissue. We measured force versus time for eight insertion depths of the catheter electrode into full-thickness endocardial samples derived from the mitral valve annulus, the left ventricular free wall and the tricuspid valve annulus. We varied the time after death at 15, 40 min, 3, 8, and 18 h and repeated our measurements. At 15 min after death, the first 0.5 mm penetration depth caused the fastest relaxation at 55 s. Force decay decreased dramatically at 15 min after death as the penetration depth increased from 0.5 to 4 mm. We used the force data sampled at 60 s after insertion to approximate the elasticity. We observed the relations between the force versus the insertion depth. The force increased by a factor of 5 for the mitral valve annulus and 8 for the left free wall from 15 min to 18 h. We derived coefficients of a second-order polynomial equation relating the force data to insertion depth with $R^2 > 0.99$.

Keywords: RF ablation; Insertion depth; Relaxation effect; Elastic component

1. Introduction

Since the mid-1980s, radio-frequency (RF) catheter ablation has treated cardiac arrhythmias of the atrioventricular junction and accessory pathways with cure rates of more than 90% (Huang and Wilber, 2000; Zipes, 1994). A catheter is placed at the region in the endocardium that is the cause of the arrhythmia and RF energy is delivered at the target site through an electrode to destroy the tissue.

Lesion size, which is the volume of nonviable tissue, is an important factor in determining the success of ablation at a given target site. Jain and Wolf (1998) found that electrode penetration depth has a significant effect on lesion size and in vitro studies have predicted lesion size for temperature-controlled mode ablation by applying a constant force, such as 10 or 20 g, for the duration of the experiment (Kongsgaard et al., 1997; Peterson et al., 1999).

To control the electrode–tissue contact by finding the relations between the force and the penetration depth, we measured the mechanical compliance of the endocardium. Previous studies have reported on mechanical properties of cardiac tissue (Broom, 1977; Halperin et al., 1987; Huyghe et al., 1991; Pinto and Fung, 1973; Strumpf et al., 1990a, b) outside the setting of RF ablation and Halperin et al. measured the transverse stiffness of the ventricular septa by penetrating a probe perpendicularly to them. Here, we used a 2.6 mm diameter ablation catheter currently in clinical use and

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measured the mechanical compliance of the endocardial regions that were considered representative of frequently ablated areas for common cardiac arrhythmias where RF ablation is clinically used as curative therapy. These include accessory pathway mediated arrhythmias (also known as Wolff–Parkinson–White syndrome) and atrioventricular nodal reentrant tachycardia. Because cardiac tissue exhibits viscoelastic characteristics, it shows relaxation of the force after a constant depth of insertion is applied. Thus, we measured the force change versus the time after applying the displacement. We controlled the time after death to determine the differences between in vitro and in vivo measurements.

2. Theory

Fung described cardiac muscle in a passive state as inhomogeneous, anisotropic and incompressible (Fung, 1981; Pinto and Fung, 1973). Its properties change with temperature, humidity and other environmental conditions and it exhibits a stress relaxation behavior under maintained stretch, called viscoelasticity. Also, cardiac tissue shows nonlinear elastic characteristics (Broom, 1977; Huyghe et al., 1991).

Sanjeevi (1982) examined the effects of relaxation of tissue and formulated an equation that considers both the elastic and viscous factors independently

$$\sigma_{\text{total}} = \sigma_{\text{elastic}} + \sigma_{\text{viscous}}. \tag{1}$$

The elastic fraction follows a second-order polynomial and we approximated the relations between the force and the penetration depth as

$$F_{\text{elastic}} = K_1 x + K_2 x^2, \tag{2}$$

where F is the force and x is the penetration depth.

3. Materials and methods

Fig. 1 shows our micrometer, electronic scale and camcorder. The 2.6 mm diameter ablation catheter was mounted on the micrometer and was moved downward by turning a screw with 0.02 mm resolution. The electronic scale (Mars Scale Corporation, MS-200) displayed the force (g) with 0.01 g resolution. We recorded the screen of the electronic scale with the camcorder for 60 s. Data were stored and later displayed for analysis (time available for each frame).

Samples were obtained from the hearts of six-week-old pigs of weight from 17 to 21 kg. Fig. 2 shows the three endocardial regions from which full-thickness tissue samples were excised. Tissue samples were derived from the mitral valve annulus, the left ventricular free wall and the tricuspid valve annulus. These endocardial regions were considered representative of frequently ablated areas for common cardiac arrhythmias where RF ablation is clinically used as curative therapy. Immediately after death the heart was rapidly removed and the areas such as the mitral valve annulus, the left ventricular free wall and the tricuspid valve annulus were excised. The thickness was 7 mm ± 0.5 mm for the tricuspid annulus approached from the right atrium, 8 mm ± 0.5 mm for the mitral valve annulus approached from the left atrium and 10 mm ± 0.5 mm for the left-free wall approached from the left ventricle.

We placed the samples on the electronic scale and, by turning the screw on the micrometer, applied a 0.5 mm penetration depth of the ablation catheter into the endocardium in 3 s. After inserting, we recorded the screen of the electronic scale with the camcorder for 60 s. We applied penetration depths from 0.5 to 4.0 mm in 0.5 mm increments. We sampled the force at 5 s and every 10 s up to 60 s after the catheter was inserted at 0.5 mm increments.

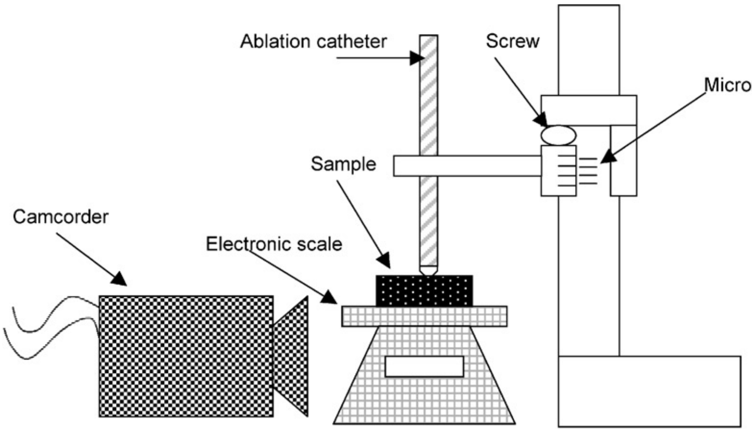

Fig. 1. To measure mechanical compliance, the screw advanced the catheter into myocardium, while the camcorder recorded the electronic scale display.

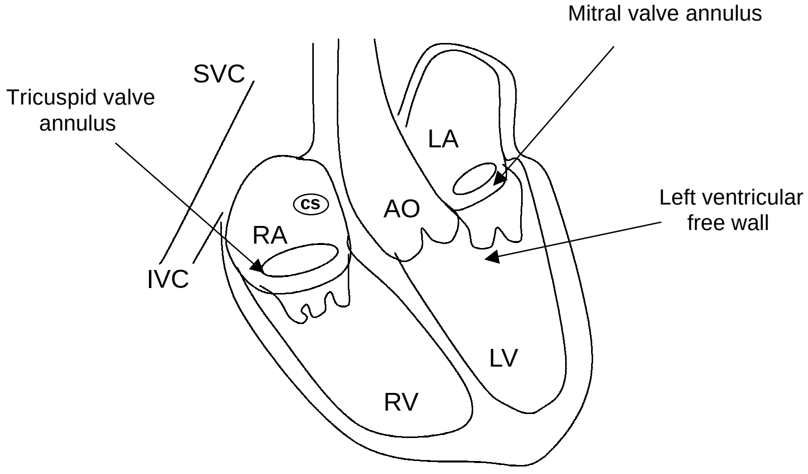

Fig. 2. We measured the mechanical compliance of three frequently ablated areas of the myocardium, which are the mitral valve annulus, the left ventricular free wall and the tricuspid valve annulus. SVC indicates superior vena cava; IVC, inferior vena cava; CS, coronary sinus; RA, right atrium; RV, right ventricle; AO, aorta; LA, left atrium; and LV, left ventricle.

The mechanical compliance of the endocardium of six samples was measured. Three samples were measured at 15 min after death and the other three at 40 min, 3, 8, and 18 h after death. All experiments were performed at room temperature. Samples were sprinkled with saline and stored in plastic wrap to keep 100% humidity between the experiments at 15, 40 min, 3, 8, and 18 h after death.

To measure the mechanical compliance of the endocardium, we measured the relations between the force and the penetration depth of the ablation catheter. Because the heart tissue exhibits viscoelasticity, those relations can be separated into relaxation and elasticity.

Relaxation: To measure relaxation, we normalized the force values to those sampled at 5 s and expressed them as a percentage with respect to the force sampled at 5 s.

Elasticity: To measure elasticity, we measured the relations between the force obtained at 60 s after the penetration depth was applied and the penetration depth. Because relaxation should disappear and only elasticity remains as the time goes to infinity, we approximate elasticity as the force at 60 s when the relaxation was less than 2% during 10 s.

Stiffness: We compared the stiffness by observing the relations between the force and penetration depths. We compared the slope of the force–displacement at each penetration depth from the graphs of the approximated second-order polynomials (Fig. 5).

We also measured the change of relaxation and elasticity due to the time after death. To determine the change of relaxation, we compared the force decay for 55 s versus the penetration depth at 15, 40 min, 3, 8 and 18 h. The force decay was expressed as the percentage change of force at 55 s with respect to the force value at 5 s after the penetration depth was applied.

To compare the relaxation effects, we used the average values of relaxation. We performed the T-test and found p values to compare the elastic responses at each time after death.

4. Results

4.1. Relaxation effects

For the mitral valve annulus and the left ventricular free wall, the first 0.5 mm penetration caused about 28% of force decay during 55 s at 15 min after death (Fig. 3). The rest of the penetration depths into the mitral valve annulus exhibited about 8–18% of relaxation and the rest of penetration depths into the left free wall about 12–14%. For the tricuspid valve annulus, 20% of the force decayed for the first 0.5 mm penetration depth during 55 s and the rest showed 10–16% of relaxation.

We compared force decay during 55 s at each location for each penetration depth at 15, 40 min, 3, 8, and 18 h after death (Fig. 4). For the mitral valve annulus, the force decay decreased from 28% to 7% at 15 min after death as the penetration depth increased but at 18 h after death, it decreased from 28% to 17%. For the left ventricular free wall, force decay decreased from 28% to 12% at 15 min after death but at 8 h after death, it decreased from 27% to 19%. The tricuspid valve annulus exhibited decreasing force decay only at 15 min after death. At 3 h after death, force decay decreased from 30% to 14% and then increased to 43%. At 3 and 8 h after death, the maximum force decay occurred at 4 mm penetration depth and it was 43% and 37%.

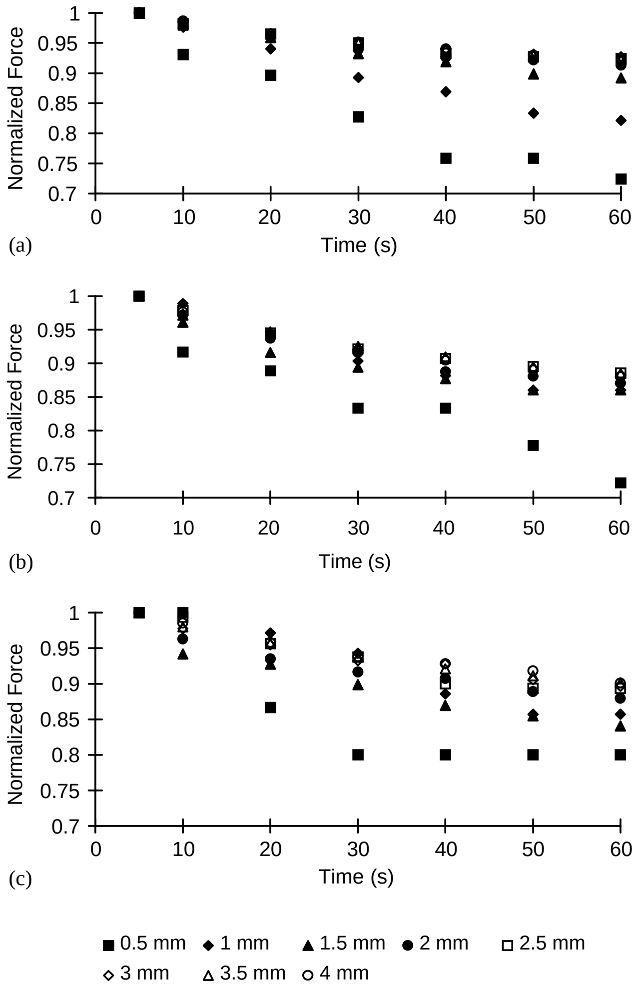

Fig. 3. We measured the relaxation effect of each area of the endocardium at 15 min after death from the average of three hearts and normalized to the 5 s force value. The first 0.5 mm penetration depth caused the fastest relaxation at all three frequently ablated areas: (a) mitral valve annulus approached from the left atrium; (b) left free wall approached from the left ventricle; and (c) tricuspid valve annulus approached from the right atrium.

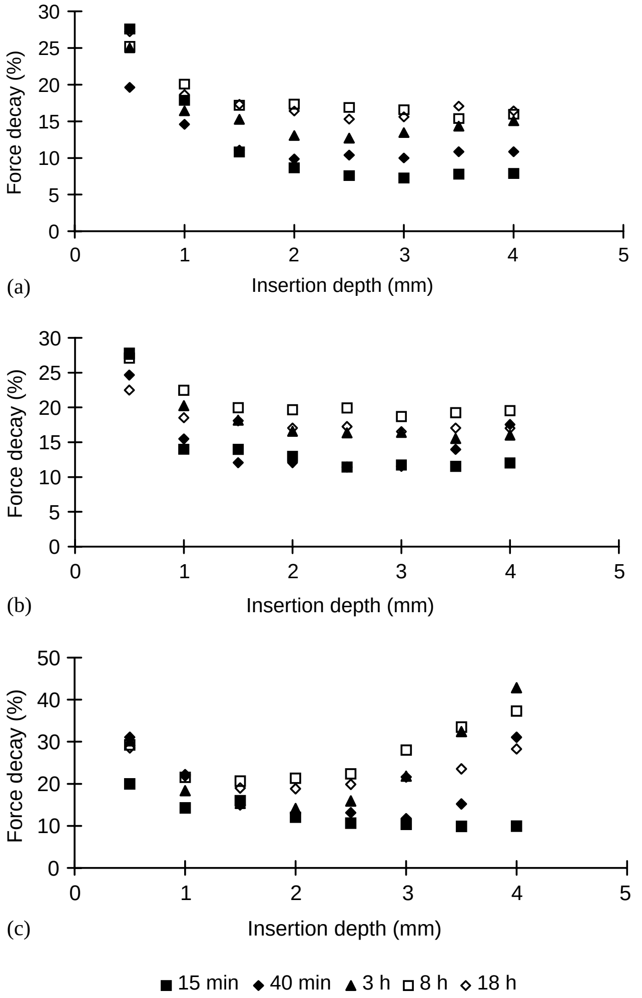

Fig. 4. We compared force decay during 55 s at each location for each penetration depth at 15, 40 min, 3, 8, and 18 h after death. At each location, force decay decreased dramatically at 15 min after death as the penetration depth increased from 0.5 to 4 mm: (a) mitral valve annulus approached from the left atrium; (b) left free wall approached from the left ventricle; and (c) tricuspid valve annulus approached from the right atrium.

4.2. Elasticity

We assumed that the force values obtained at 60 s after each additional penetration depth was applied represented elastic responses. An elastic response does not change with time and is expressed by the relation between the force and the penetration depth, which is called stiffness.

We compared the elastic force data at 15 min after death with those at 40 min, 3, 8 and 18 h after death (Fig. 5). The forces at 15 min did not show a significant difference from those at 40 min but the forces at 3, 8, and 18 h exhibited greater values ($p<0.01$). When we compared the forces at 3 h after death with those at 18 h after death, the forces at 18 h after death exhibited greater values ($p<0.01$). The stiffness of the mitral valve annulus increased by a factor of 5 from 15 min to 18 h and the stiffness of the left free wall increased by a factor of 8. The tricuspid valve annulus also showed stiffer characteristics as time increased after death. When we compared the forces at 15 min after death with those at 40 min after death, the forces at 40 min after death exhibited greater values ($p<0.01$) by a factor of 2. Though the averages of the forces exhibited greater values at 8 and 18 h after death, they did not show significant differences from other forces at 15, 40 min and 3 h ($p>0.05$).

We approximated the relation between the force and the penetration depth to a second-order polynomial. We derived the coefficients in each portion at 15 min after death using the average of the force data and obtained $R^2>0.99$, which confirms the

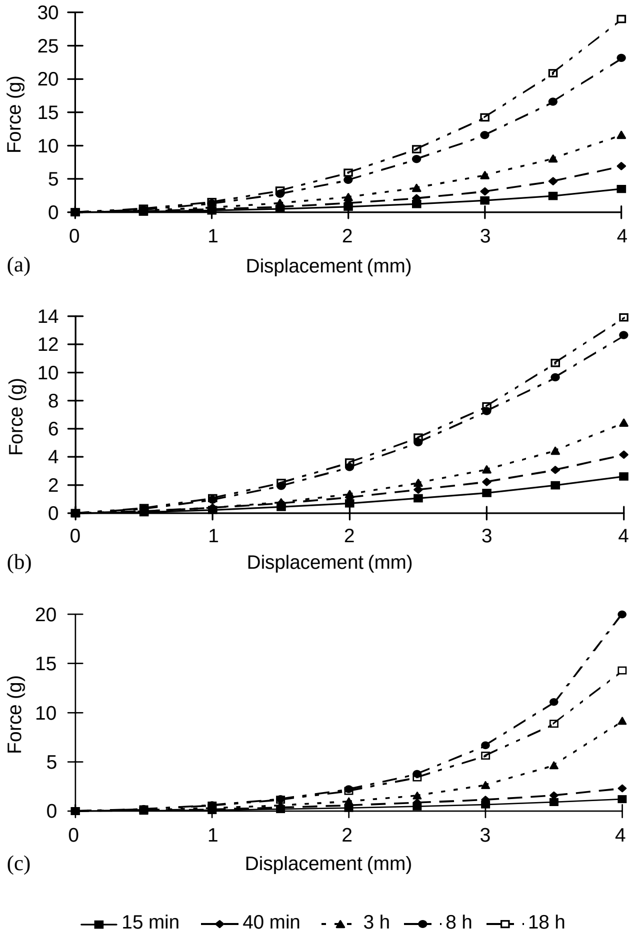

Fig. 5. We measured elasticity of each area of the endocardium at 15, 40 min, 3, 8, and 18 h after sacrifice. Elastic forces increased at all three locations as the time after death increased: (a) mitral valve annulus; (b) left free wall; and (c) tricuspid valve annulus.

Table 1
The coefficient database of K_1 and K_2 of each area of the endocardium at 15 min after sacrifice ($R^2 > 0.99$)

Name of the area of the endocardium	K_1	K_2
Mitral valve annulus	0.1463	0.0578
Left free wall	0.2173	−0.0305
Tricuspid valve annulus	0.0701	0.0177

assumption. Table 1 lists the coefficients, K_1 and K_2 for Eq. (2).

5. Discussion

Because the electrode–tissue contact has a significant effect on lesion size, we measured the mechanical compliance of three frequently ablated areas by using an RF ablation catheter to control the penetration depth. To compare the mechanical properties in vivo and in vitro without any treatment, we tried to obtain samples as soon after death as possible, which was at 15 min after death. Previous in vitro studies on RF ablation performed the tests with the tissues dipped in saline (Kongsgaard et al., 1997; Peterson et al., 1999) so we used saline to preserve the samples at 100% humidity. We considered that the data at 15 min after death were most close to those in vivo and the rest were those in vitro without treatment.

Approximating elastic forces at 60 s after the penetration, we found that elastic forces at each penetration depth increased at all three locations as the time after death increased (Fig. 5). As the heart tissues were kept at 100% humidity without any specific treatment and the time after death increased, we found that the stiffness increased significantly, which was significantly different from that in vivo. This result shows the importance of using fresh samples to obtain an accurate relation between the force and the penetration depth, which is important for experiments of RF ablation in vitro.

Acknowledgements

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