Admittance to detect alterations in left ventricular stroke volume

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BACKGROUND Implantable cardioverter-defibrillators monitor intracardiac electrograms (EGMs) to discriminate between ventricular and supraventricular tachycardias. The incidence of inappropriate shocks remains high because of misclassification of the tachycardia in an otherwise hemodynamically stable individual. Coupling EGMs with an assessment of left ventricular (LV) stroke volume (SV) could help in gauging hemodynamics during an arrhythmia and reducing inappropriate shocks.

OBJECTIVE The purpose of this study was to use the admittance method to accurately derive LV SV.

METHODS Ultrasonic flow probe and LV endocardial crystals were used in canines (n = 12) as the standard for LV SV. Biventricular pacing leads were inserted to obtain admittance measurements. A tetrapolar, complex impedance measurement was made between the Bi-V leads. The real and imaginary components of impedance were used to discard the myocardial component from the blood component to derive instantaneous blood conductance (G_b). Alterations in SV were measured during right ventricular pacing, dopamine infusion, and inferior vena cava occlusion.

RESULTS G_b tracks steady-state changes in SV more accurately than traditional magnitude (ie, |Y|, without removal of the muscle signal) during right ventricular pacing and dopamine infusion ($P =$ .004). Instantaneous LV volume also was tracked more accurately by G_b than |Y| in the subset of subjects that underwent inferior vena cava occlusions (n = 5, $P =$ .025). Finite element modeling demonstrates that admittance shifts more sensitivity of the measurement to the LV blood chamber as the mechanism for improvement (see Online Appendix).

CONCLUSION Monitoring LV SV is possible using the admittance method with biventricular pacing leads. The technique could be piggybacked to complement EGMs to determine if arrhythmias are hemodynamically unstable.

KEYWORDS Shock reduction; Biventricular pacing/defibrillation; Ventricular tachycardia; Ventricular fibrillation; Inappropriate shocks

ABBREVIATIONS **2D** = 2-dimensional; **AICD** = automatic implantable cardioverter-defibrillator; **EGM** = electrogram; **FEM** = finite element method; $\mathbf{G_b}$ = blood conductance from the admittance method; **HR** = heart rate; **ICD** = implantable cardioverter-defibrillator; **IVCO** = inferior vena cava occlusion; **LCV** = left coronary vein; **LV** = left ventricle; **RA** = right atrium; **RV** = right ventricle; **RVA** = right ventricular apex; **SV** = stroke volume; **Y** = complex admittance (inverse of impedance); **|Y|** = magnitude of admittance; **Z (Ω)** = complex impedance

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Introduction

Automated implantable cardioverter-defibrillators (AICDs) monitor intracardiac electrograms (EGMs) to discriminate between ventricular and supraventricular tachycardias. Hemodynamically unstable arrhythmias are treated with high-energy shocks, whereas benign arrhythmias are treated conservatively. Unfortunately, modern defibrillators cannot always reliably differentiate between these situations and sometimes deliver inappropriate shocks. Spurious shocks result in battery depletion and increased patient morbidity, and can cause degeneration of benign cardiac arrhythmias.[1] An advancement in which AICDs couple EGMs with beat-by-beat assessment of left ventricular (LV) stroke volume (SV) could discriminate between hemodynamically unstable and stable arrhythmias. In such a scheme, AICD shocks would be reserved for

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hemodynamically unstable arrhythmias, which should prevent inappropriate AICD shocks.

The use of electric fields to measure cardiac physiology has been plagued by myocardial noise contaminating the desired LV blood volume signal, limiting clinical applicability. We have derived a new method to remove the myocardium, which we term *admittance*. Admittance inputs a current into the myocardium and takes advantage of the capacitive nature of electrical gradient across myocytes, whereas blood has no capacitive properties. The returning voltage signal has a phase shift that can be used to separate the blood and myocardial components of the signal. In this study of large mammalian hearts, we focused on removing the myocardial signal and obtaining pure blood volume to derive LV SV via commercially available pacemaker and implantable cardioverter-defibrillator (ICD) leads. Future studies will focus on incorporating the pure LV SV obtained by admittance in the classification of arrhythmias as hemodynamically unstable or stable.

By obtaining pure LV SV, we propose that admittance can aid AICD classification of arrhythmias as hemodynamically unstable or stable, through the estimation of LV SV on a beat-by-beat basis.[2,3] In this article, we describe a new technique that measures the impedance between the right ventricular (RV) and lateral coronary vein (LCV) leads by applying a current between the RV and LCV ring electrodes and measuring the returning voltage between the RV and LCV tip electrodes (Figure 1). Although conductance has been used to estimate intraventricular blood volume,[4] the admittance method represents a substantial improvement because it uses the complex nature of tissue's electrical properties to separate and discard the myocardial component, leaving only the LV blood signal.[2] At a frequency of 20 kHz, muscle exhibits significant permittivity,[5] whereas the blood's permittivity (or capacitance) is negligible. The current study demonstrates that admittance can accurately measure SV using commercial leads in large animal hearts. These results were confirmed by finite element modeling analysis (see Online Appendix). The modeling studies explain how admittance can accurately determine LV SV compared with conductance. Algorithms that incorporate LV SV obtained via admittance to assist AICD in differentiating malignant from benign arrhythmias will require future explorations and validations.

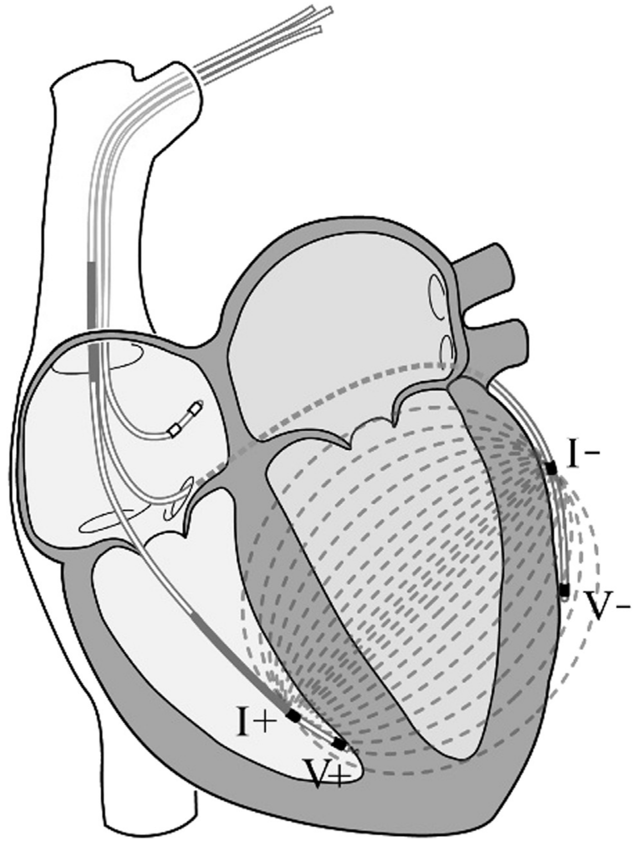

Figure 1 Leads tips were placed across from each other in a configuration with the right ventricular (RV) and left ventricular (LV) electrodes on the RV mid-septal and LV lateral epicardial walls, respectively. Current (I) flows from the RV to the LV ring electrodes and voltage (V) is measured from the corresponding electrode tips. This returning voltage signal and the applied current were used to derive admittance. In this way, admittance was then used to obtain the LV stroke volume (SV) by a cross LV chamber tetrapolar impedance measurement using custom instrumentation. Leads placed in this configuration were ideal for obtaining LV blood volume measurements because blood has 5 times lower resistivity than myocardium and the preferential path for current flow is the LV blood volume, as illustrated by the *dashed lines.*

Methods

Animal preparation

All experiments were approved by the Institute for Animal Care and Use Committee at the University of Texas HSC at San Antonio. Twelve canines (weight 21–35 kg) were anesthetized using a mixture of ketamine and diazepam at a dosage of 1 cc per 5 kg. Anesthesia was maintained with 2.5% isoflurane with 100% oxygen. To obtain blood pressure, a microtip pressure sensor (Transonic, Ithaca, NY) was placed in the femoral artery. Two different accepted methods were used to obtain LV SV and volumes as controls: an aortic ultrasonic flow probe and 2-dimensional (2D) endocardial ultrasonic crystals, respectively.[6] A thoracotomy was performed to place the ultrasonic flow probe (Transonic) around the ascending aorta. Four ultrasonic crystals (Sonometrics, London, Ontario, Canada) were inserted into the endocardium in the anterior–posterior and apex–base planes to measure LV dimensions. For the admittance measurement, commercial pacing leads (QuickFlex, Tendril ST, and Tendril DX, St. Jude, St. Paul, MN) were placed under fluoroscopic guidance into the RV, right atrial (RA) appendage, and lateral coronary vein (LCV).

In order to obtain an isolated LV blood volume signal, epicardial muscle property measurements are required for incorporation into our previously published equations[3] to identify and remove the myocardial component from the combined myocardium–blood admittance signal. LV muscle conductivity and permittivity were obtained with a tetrapolar probe[3,5] placed on the anterior surface of the LV at a location avoiding the left anterior descending artery and its branches,