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Seismocardiography and 4D Flow MRI Reveal Impact of Aortic Valve Replacement on Chest Acceleration and Aortic Hemodynamics

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Abstract

Aortic valve replacement (AVR) is a common treatment for severe aortic valve disease, which can adversely affect blood flow in the aorta. Seismocardiography (SCG) measures physical vibrations at the exterior of the chest, which can be sensitive to altered cardiac function and flow dynamics. MRI can image blood movement, and it can provide depiction and quantification of aortic flow. Here we present SCG and MRI measurements from before and after AVR and ascending aorta replacement, in the case of a woman with bicuspid aortic valve disease and a dilated ascending aorta. SCG measurements show elevated energy during systole indicating stenotic flow before surgery and lowered systolic energy levels after replacement with a prosthetic valve. MRI shows jetting, helical flow before surgery and cohesive flow after.

Keywords

bicuspid aortic valve; valve repair/replacement; aorta and great vessels; seismocardiography (SCG); magnetic resonance imaging (MRI)

Introduction

Surgical replacement of the aortic valve and ascending aorta is a common treatment for severe aortic valve disease in the presence of aortic dilation. However, given the potential for vessel wall compliance mismatch, overt changes to aortic blood flow can occur, along with exacerbated valve opening and closing sounds. These effects are sometimes noticeable by the patient.

Seismocardiogram (SCG) signals capture physical reverberations of the exterior chest wall originating from the beating heart, pulsating vessels and accelerating blood flow. Observed

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Author Contributions

EJ, CM, PM, MM, AB contributed to data analysis/interpretation. ME, MM, AB contributed to concept/design. EJ, MM, AB contributed to drafting. CM, PM contributed to critical revision. CM, AB contributed to data collection. EJ, ME, MM, AB contributed to securing funding.

changes in the SCG signal have been associated with cardiac parameters of clinical interest, such as reduced left-ventricular function (1) or development of coronary artery disease (2), but current clinical applications of SCG are limited. Cardiac imaging with cine MRI provides complementary, dynamic depictions of the beating heart and vessels to quantify cardiac function, and 4D flow MRI can augment this by measuring blood velocities to assess characteristics of aortic flow. MRI can be used to assess hemodynamics directly relevant to valvulopathy and aortopathy, e.g., peak velocity in aortic stenosis (3) and wall shear stress pre-/post-aortic valve repair and/or aortic replacement (4). Here, we present a combined MRI and SCG study, performed pre- and post-prophylactic replacement of an ascending aortic aneurysm and stenotic bicuspid aortic valve (BAV) with a mechanical valve and graft.

Case Report

A 72-year-old female diagnosed at echocardiography three weeks prior with a dilated ascending aorta (4.3 cm diameter) and BAV disease (peak velocity 440 cm/s, EOA 0.6 cm²) was prospectively enrolled in an IRB-approved study performing SCG and MRI in volunteer subjects. Imaging and SCG were collected one day before the subject underwent mini-sternotomy aortic valve replacement (AVR), ascending aorta replacement, and primary closure of a patent foramen ovale. The diseased BAV and aorta were replaced with a separate mechanical valve (23 mm Cryolife On-X Aortic Heart Valve with Conform-X sewing ring) and woven Dacron graft (26 mm Terumo Vascutek Gelweave). Measurements were collected again one year later.

MRI included cine SSFP in the 2-, 3-, 4-chamber, left-ventricular outflow tract, and enface aortic valve views and 4D flow MRI with full thoracic aorta coverage (5). SCG recordings were collected in the supine position at the sternum (Figure 1), immediately prior to MR scans. A custom-built wearable device measuring ECG voltages and physical accelerations recorded the SCG (6). Acceleration frequencies up to 250 Hz were recorded, above the typical SCG range. The beat-averaged SCG signal and spectrogram, which shows time-varying frequency content of the chest accelerations, were computed. Valve opening, end systole, and valve closing times were annotated in cine MRI. Time-resolved pathlines were generated to visualize blood velocities measured by 4D flow MRI.

Before AVR, cine imaging depicts the stenotic aortic valve (Figure 2 A). The peak SCG accelerations occur during rapid ejection and are within a normal range of 100–200 mm/s². However, the SCG spectrogram shows a sustained acceleration energy in the high-frequency bands of 120–240 Hz, starting mid-systole and ending end-systole (Figure 2 B). From mid-to end-systole, the average high-frequency band SCG energy is 0.52 mm/s². This energy corresponds in cardiac cycle time to flow jets and helical flow depicted by 4D flow pathlines (Figure 2 C). Peak velocity measured by 4D flow in a volume of interest near the aortic valve rises to 343 cm/s and remains above 300 cm/s for most of systole.

After surgery, cine images show the valve assembly, characterized by hypointense signal from the short- T_2^* material of the prosthetic valve (Figure 2 A). The peak SCG acceleration magnitudes are similar to those before AVR, also within 100–200 mm/s, but the duration of positive chest acceleration during rapid ejection is extended by 20%, from 29 ms before

replacement to 35 ms (Figure 2 B). In the second half of systole, the average high-frequency SCG energy (that before replacement corresponded with helical flow in MRI) is reduced by 46% to 0.28 mm/s², and 4D flow MRI pathlines depict largely cohesive flow without jet patterns (Figure 2 C). Maximal peak velocity in the ascending aorta observed during systole is 161 cm/s. Intensified reverberation occurs at aortic valve close (Figure 2 B), with more high-frequency energy. For example, maximal jerk (acceleration time-derivative) at aortic close with the prosthetic valve is 9.0 m/s³, 36% higher than 6.6 mm/s³ before replacement, and SCG acceleration energy at aortic close averaged over 60–240 Hz is 0.95 mm/s², or 66% higher.

Discussion

Comparison of MRI and SCG data before and after AVR and graft implantation allowed quantification of changes to aortic flow and valve dynamics. Pathological flow from the stenosed, bicuspid aortic valve was resolved after surgery. Before replacement, peak velocity in 4D flow MRI indicated stenotic flow. The presurgical peak transvalvular velocity was lower with MRI than the earlier echocardiography measurement due to partial voluming and a lower temporal resolution of MRI. Jetting and helical flow during peak systole are known features of BAV, and their presence corresponded with SCG chest vibration measurements showing abnormal high-frequency energy. After replacement, abnormal chest vibrations were not present, peak velocity measurements did not indicate stenosis, and the pathological flow patterns were resolved. However, a more energetic valve closing resulted from the prosthetic valve closure. The graft material is known to have lower compliance compared to native tissue and will not damp the closing reverberations as much as native tissue does. These altered vessel compliance and valve-closure dynamics were noticeable in the SCG acceleration spectrogram. Taken together, 4D flow MRI and SCG chest acceleration measurements may provide complementary insights into blood flow alterations and patient-reported physical sensations after aortic valve surgical procedures. Generally, evaluation by 4D flow MRI after AVR reveals the hemodynamic effects of the valve replacement, it may potentially be used to assess the degree to which pathology has been resolved. However, MRI can be time-consuming. Acquiring SCG requires minimal training, in contrast to echocardiography, and the material costs are modest (around 100 USD). Here, the SCG signal gives clear indication that valve-mediate flow pathology was resolved by AVR, suggesting its use as an adjunct, two-minute post-operative exam to assess potential need for more comprehensive evaluation. Additional investigation is required to evaluate potential influence of subject BMI upon SCG, but effects are expected to be modest.

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Figure 1.
A custom wearable cardiac monitoring device recording ECG and chest accelerations recorded the supine SCG at the sternum.

Figure 2.

MRI and SCG measurements taken before and after bicuspid aortic valve replacement. (A, *left*) Still frames from cine MRI of the aortic valve and left-ventricular outflow tract before replacement show the stenotic aortic valve and a characteristic jet in the ascending aorta (AAo). (B, *left*) the SCG signal and 4D flow MRI measurements capture the effects in the AAo of the stenotic flow across the aortic valve. (C, *left*) Pathline visualizations from 4D flow MR depict a flow jet near the valve and swirling flow near the arch. (A,B,C, *right*) Images and measurements after replacement of the bicuspid valve with a synthetic valve are

more characteristic of normal flow and function, with the exception of elevated SCG energy at aortic valve closure.

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