Modeling Seismocardiographic Signal using Finite Element Modeling and Medical Image Processing

Peshala T. Gamage, Md Khurshidul Azad, Richard H. Sandler, Hansen A. Mansy

Biomedical Acoustic Research Lab, University of Central Florida, Orlando, Florida, USA
{peshala@knights., khurshid@knights., hansen.mansy}@ucf.edu

Introduction- Seismocardiography (SCG) is the measurement of the chest surface accelerations that are primarily produced by a combination of mechanical activities of the heart, such as valve closures and openings, blood momentum changes and myocardial movements [1-3]. The complex nature of these processes has made it challenging to relate the morphology of the SCG signal to its genesis. Certain studies have used medical imaging to identify several feature points of the SCG signal by correlating their occurrence time with the corresponding cardiac events seen in imaging [4, 5]. However, these findings remain inconclusive [6]. The localized movements (i.e. valve openings and closures, ventricular contractions, blood flow accelerations etc.) may superimpose causing complex movements where original movements may amplify or nullify as they reach the chest surface and affect SCG morphology. Hence, SCG signal can also be described as the propagated vibrations generated by individual sources (i.e., valve closures and openings, blood flow accelerations). These vibrations displace their more immediate boundaries (e.g., pericardium, Aorta wall) and surrounding tissues (e.g. lung tissue, ribs, chest wall muscle and skin) before they are detected at the chest surface. Hence, modeling the propagation of overall cardiac wall motion to the chest surface may help enhance our understanding of SCG genesis.

Methods -A simplified 2D computational model was used to simulate the propagation of cardiac wall motion to the chest surface. Initially, the 2D computational model was selected to avoid the significantly higher computational complexity of 3D models. The current approach can, however, be extended to future 3D models. This computational model was implemented in ANSYS (ANSYS Inc, Canonsburg, PA) transient structural analysis module, which uses finite element method (FEM). FEM discretizes the structural domain into small (finite) elements, which are assembled to implement the required boundary conditions and interfaces between the model components. The displacements and forces acting on each element are described by the equation of motion. The equations from all the elements are combined to form a system of equations, which is then solved to find the displacement of all elements in the domain. This analysis provides useful information about propagation of heart movements to the chest surface, which in turn, will increase our understanding of the genesis of SCG signals. The computational geometry and boundary conditions were extracted from a cardiac cine-MRI imaging sequence available in DICOM format. As shown in Fig. 1, the proposed simplified geometry included the lung and the surrounding tissue regions. Linear elastic material properties were assumed, and the transient displacement boundary conditions were defined on the boundaries shown in Fig. 1 (b). These boundary movements were extracted from MRI images by tracking the movement using Kanade-Lucas-Tomashi (KLT) tracker [7] implemented in MATLAB. KLT tracker captures the movement of the boundaries by analyzing and optimizing the similarity between the image intensities frame by frame.

Results- The Left ventricle (LV) volume was calculated from the blood pool area in the LV using the grayscale intensity of the MRI image (Fig.1 (c)). The LV waveform is shown in Fig 2(b) for one cardiac cycle. Cardiac features (Aortic Opening (AO), Aortic Closure (AC) and Mitral Closure (MC) were estimated from the LV waveform and are shown in Fig 2(b). The simulated acceleration signal reaching the chest surface is also shown in Fig 2. (b). This signal had features (i.e. , AO, AC and MC) comparable to those observed in SCG waveforms described in previous studies[4, 5]. In addition, the timing of LV volume change in relation to the SCG signal (Fig. 2 (b)) was also consistent with the literature [6]. These results suggest that an FEM model may be useful in simulating the propagation of cardiac mechanical movement reaching the chest surface.

Future work- Future work involves further validating the method by comparing the measured SCG and simulated SCG waveform of the same subject. Due to the pilot nature of the study, linear material properties were assumed. Future work will include more realistic material properties (for Lung, chest wall, etc.), incorporating the rib cage into the model. Furthermore, the method can be extended to 3D with the use of 4D MRI imaging, which allows capturing 3-dimensional heart and boundary movements.

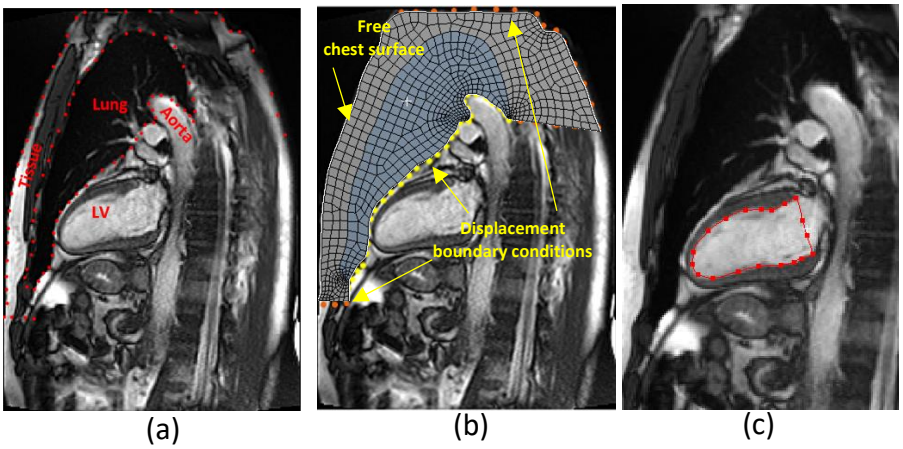


Figure 1: (a) MRI image of the 2-chamber view of the heart with surrounding lung and tissue regions (b) Computational mesh with boundary conditions. (Points specified in yellow color had larger movements relative to the points specified in orange color since they capture the movements due to the blood pumping of left ventricle and aortic blood flow accelerations. Although the points specified in orange color had smaller movements, they were tracked to provide more realistic boundary conditions to the computational model. The boundary on the chest tissue surface allowed to move freely) (c) Blood pool area in the left ventricle.

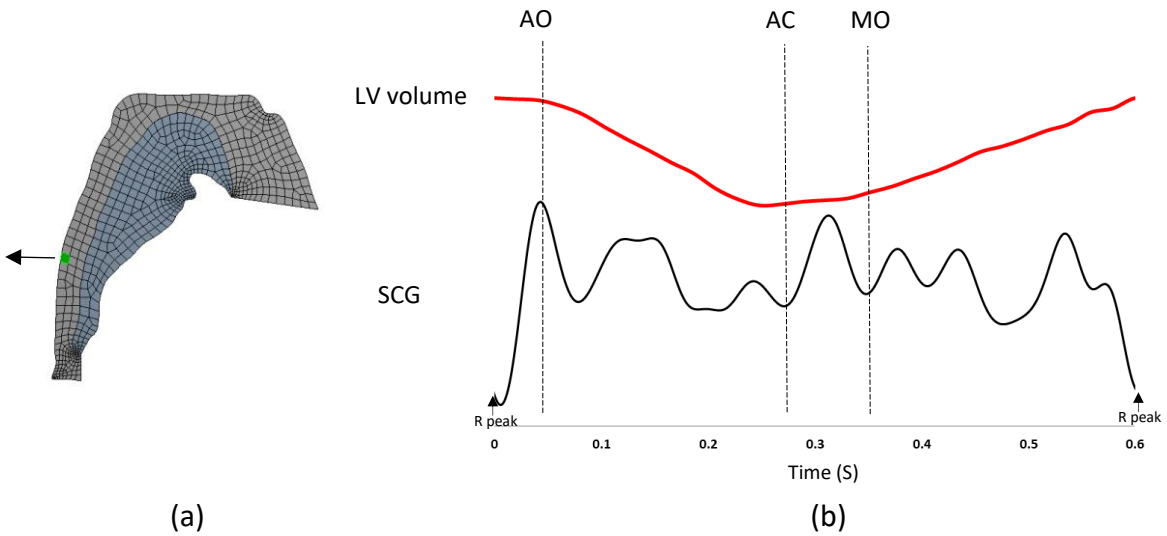


Figure 2: (a) The FEM model domain along with the location and direction of the SCG measurement (b) Simulated SCG morphology with the approximated LV volume variation. Here, SCG heartbeat is plotted in R-R ECG peaks interval. Features corresponding to aortic opening (AO), aortic closure (AC) and mitral opening (MO) were identified in the simulated SCG waveforms with their LV. volume variation.

REFERENCES

[1] V. Gurev, K. Tavakolian, J. Constantino, B. Kaminska, A. P. Blaber, and N. A. Trayanova, "Mechanisms underlying isovolumic contraction and ejection peaks in seismocardiogram morphology," *Journal of Medical and Biological Engineering*, vol. 32, p. 103, 2012.

[2] P. T. Gamage, M. K. Azad, A. Taebi, R. H. Sandler, and H. A. Mansy, "Clustering Seismocardiographic Events using Unsupervised Machine Learning," in *2018 IEEE Signal Processing in Medicine and Biology Symposium (SPMB)*, 2018, pp. 1-5.

[3] A. Taebi, B. E. Solar, A. J. Bomar, R. H. Sandler, and H. A. Mansy, "Recent Advances in Seismocardiography," *Vibration*, vol. 2, pp. 64-86, 2019.

[4] L. Giorgis, A. Hernandez, A. Amblard, L. Senhadji, S. Cazeau, G. Jauvert, *et al.*, "Analysis of cardiac micro-acceleration signals for the estimation of systolic and diastolic time intervals in cardiac resynchronization therapy," in *Computers in Cardiology, 2008*, 2008, pp. 393-396.

[5] R. S. Crow, P. Hannan, D. Jacobs, L. Hedquist, and D. M. Salerno, "Relationship between seismocardiogram and echocardiogram for events in the cardiac cycle," *American journal of noninvasive cardiology*, vol. 8, pp. 39-46, 1994.

[6] A. Akhbardeh, K. Tavakolian, V. Gurev, T. Lee, W. New, B. Kaminska, *et al.*, "Comparative analysis of three different modalities for characterization of the seismocardiogram," in *Conference Proceedings*, 2009, p. 2899.

[7] C. Tomasi and T. K. Detection, "Tracking of point features," Tech. Rep. CMU-CS-91-132, Carnegie Mellon University1991.

Modeling Seismocardiographic Signal using Finite Element Modeling and Medical Image Processing

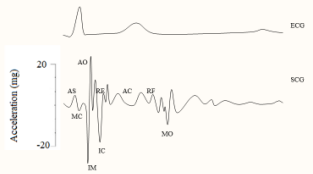
Peshala T. Gamage, Md Khurshidul Azad, Richard H. Sandler, Hansen A. Mansy
Department of Mechanical and Aerospace Engineering, University of Central Florida, Orlando, FL

UCF College of Engineering and Computer Science

Biomedical Acoustics Research Lab

Background

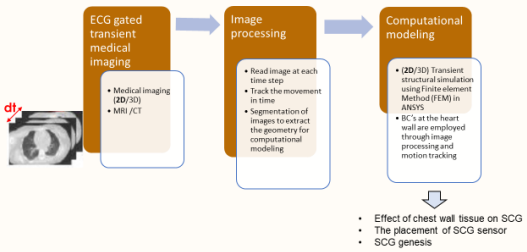
- **Seismocardiography (SCG) is the measurement of the chest surface accelerations that are primarily produced by a combination of mechanical activities of the heart, such as valve closures and openings, blood momentum changes and myocardial movements.**
- **The complex nature of these processes has made it challenging to relate the morphology of the SCG signal to its genesis.**
- **Certain studies have used medical imaging to identify several feature points of the SCG signal by correlating their occurrence time with the corresponding cardiac events seen in imaging. However, these findings remain inconclusive.**



The cardiac events identified in the SCG signal as proposed by Crow et al(1994).The abbreviations are: AS-atrial systole, MC-mitral valve closure, IM-isovolumic movement, AO-aortic valve opening, IC-isotonic contraction, RE- rapid ejection, AC- aortic valve closure, MO-mitral valve opening, RF- rapid filling

- **The localized movements (i.e. valve openings and closures, ventricular contractions, blood flow accelerations etc.) may superimpose causing complex movements where original movements may amplify or nullify as they reach to the chest surface and affect SCG morphology.**
- **SCG signal can also be described as the propagated vibrations generated by individual sources (i.e., valve closures and openings, blood flow accelerations). These vibrations displace their more immediate boundaries (e.g., pericardium, Aorta wall) and surrounding tissues (e.g. lung tissue, ribs, chest wall muscle and skin) before they are detected at the chest surface.**
- **Modeling the propagation of overall cardiac wall motion to the chest surface may help enhance our understanding of SCG genesis.**

Method



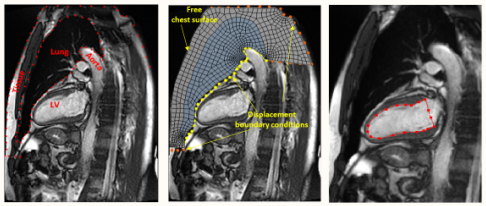
Method: Image processing

- **The computational geometry and boundary conditions were extracted from a cardiac cine-MRI imaging sequence (with 30 frames per heart cycle) available in DICOM format.**
- **Heart wall movements were extracted from MRI images by tracking the movement using Kanade-Lucas-Tomashi (KLT) tracker implemented in MATLAB.**
- **KLT tracker algorithm:** Input image $I(\mathbf{x})$
  Reference image $T(\mathbf{x})$
  - The best alignment minimizes image dissimilarity $\sum_{\mathbf{x}}[I(W(\mathbf{x};p)) - T(\mathbf{x})]^2$
  - Assume a warping function $W(\mathbf{x};p)$ where p is a vector of parameters.

    Ex: For translations $W(\mathbf{x};p) = (x + b_1, y + b_2)$
  - Find the Δp vector which minimizes the dissimilarity $\sum_{\mathbf{x}}[I(W(\mathbf{x};p+\Delta p)) - T(\mathbf{x})]^2$
  - Points from $I(\mathbf{x})$ to $T(\mathbf{x})$ can be tracked with the warping function $W(\mathbf{x};p+\Delta p)$

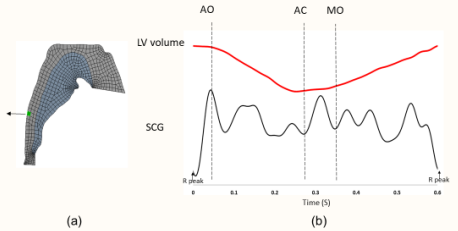
Method: Computational modeling

- **Computational model was implemented in ANSYS transient structural analysis module (ANSYS Inc., Canonsburg, PA), which uses finite element method (FEM).**
- **FEM discretizes the structural domain into small (finite) elements, which are assembled to implement the required boundary conditions and interfaces between the model components.**
- **The displacements and forces acting on each element are described by the equation of motion. The equations from all the elements are combined to form a system of equations, which is then solved to find the displacements of all elements in the domain.**



(a) MRI image of the 2-chamber view of the heart with surrounding lung and tissue regions (b) Computational mesh with boundary conditions. (Points specified in yellow color had larger movements relative to the points specified in orange color since they capture the movements due to the blood pumping of left ventricle and aortic blood flow accelerations. Although the points specified in orange color had smaller movements, they were tracked to provide more realistic boundary conditions to the computational model. The boundary on the chest tissue surface allowed to move freely) (c) Blood pool area in the left ventricle (LV).

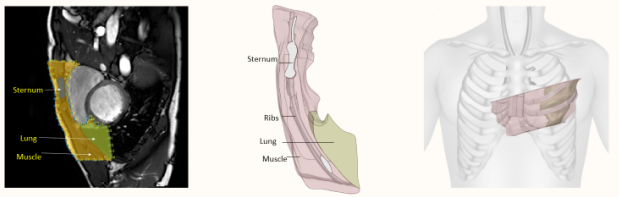
Results



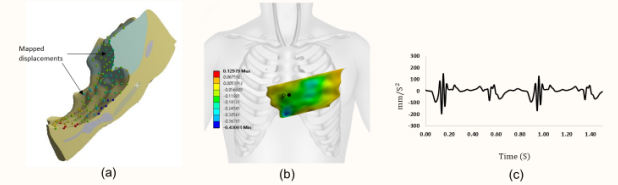
(a) The FEM model domain along with the location and direction of the SCG measurement (b) Simulated SCG morphology with the approximated LV volume variation. Here, SCG heartbeat is plotted in R-R ECG peaks interval. Features corresponding to aortic opening (AO), aortic closure (AC) and mitral opening (MO) were identified in the simulated SCG waveforms with their LV volume variation.

Ongoing & future work

- **Computational modeling of SCG in 3D**



(a) Representation of the simplified computational domain on a short-axis MRI image (b) Extracted 3D computational domain from short-axis MRI images with ribs (c) Placing the computational domain on the chest.



(a) Mapped displacements on the heart wall boundary captured from 3D motion tracking (b) Spatial distribution of displacement in ventral direction (in mm) at end systole (c) Simulated acceleration measured at point P in ventral direction for two heart cycles.

References

[1] R. S. Crow, P. Hannan, D. Jacobs, L. Hedquist, and D. M. Salerno, "Relationship between seismocardiogram and echocardiogram for events in the cardiac cycle," American journal of noninvasive cardiology, vol. 8, pp. 39-46, 1994.
[2] C. Tomasi and T. K. Detection, "Tracking of point features," Tech. Rep. CMU-CS-91-132, Carnegie Mellon University,1991.