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Structured Light Imaging of Epicardial Mechanics

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In 1930, Carl Wiggers used “moving pictures” technology to study complex cardiac motion during fibrillation in the canine heart.¹ By repeatedly analyzing frame after frame, he was able to comprehend and precisely describe the mechanisms of initiation and development of ventricular fibrillation (VF), induced by electric shock. This cinematographic imaging presented evidence of several stages of VF progression, now known as the Wiggers Stage 1, Wiggers Stage 2, etc.² Today, the elegant observations of Wiggers can be greatly enhanced using novel advances in 3-D imaging technology and image registration algorithms.

Recently, we have developed a real-time 3-D imaging system based on a digital fringe projection technique.³ In this study, we employed a faster imaging system consisting of a DLP Discovery 4100 projector (Texas Instrument, TX) and a defocusing technique to greatly improve imaging speed. Briefly, three spatially shifted binary structures are sent to the properly defocused projector to generate phase-shifted fringe patterns. Each 3-D “frame” is recorded as three images by a high-speed CMOS camera (Phantom V9.1, Vision Research, NJ) at 333 frames per second (FPS), which is calibrated and synchronized with the projector. Using the recovered phase to establish correspondences between the camera image and the projector, the coordinates of each pixel can be calculated and used to form a 3-D shape.

Using this system, we imaged Langendorff-perfused hearts isolated from New Zealand white rabbits (n= 4). The animal protocol was approved by the Institutional Animal Care and Use Committee of Washington University in St. Louis. Each heart was removed via a mid-sternal thoracotomy and perfused with oxygenated (95% O₂, 5% CO₂) Tyrode’s solution under a constant pressure of 60 mmHg and temperature of 30 °C. Hypothermia was used to adjust physiological dynamics for the current frame rate of the structured light system. A faster system with up to 10,000 FPS is under development.

Figure 1, Movie 1, and Movie 2 demonstrate a representative example of data recorded by the structured light system from the anterior aspect of the heart. Using the three-fringe method, a high-resolution mesh of the epicardial surface in the field of view was created (Figure 1B). Using a custom MATLAB (Mathworks, Natick, MA) routine, this surface is then interpolated (Figure 1C) and wrapped with the original texture map (Figure 1D). By combining the texture map and the interpolated mesh, surface geometry and surface characteristics are preserved in a detailed 3-D model. If a cross-section is removed from the model, the full 3-D characteristics of the epicardium can be easily observed (Figure 1E).

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Due to its ability to produce real-time shape measurements with high spatial and temporal resolution, structured light allows for precise tracking of epicardial contraction and relaxation in three dimensions. For this study, we created a motion-tracking algorithm in MATLAB using the well-established window-offset method.⁴ In general, our algorithm describes planar translation of a time series of images relative to a specific reference. Figure 1 demonstrates motion tracking at two arbitrarily selected locations at the apex (red) and the left ventricle (green) through systole and diastole in 2-D (Figure 1A) and 3-D (Figures 1C, D) during sinus rhythm.

Here, we present proof of concept data for structured light imaging as an emerging imaging modality that addresses several unmet needs in both basic and clinical cardiology. Our structured light system allows for precise tracking of epicardial motion and strain that could advance mechanical studies of excitation-contraction coupling, mechano-electric feedback, mechanical asynchrony due to cardiomyopathy or right ventricular pacing, and resynchronization therapy. Additionally, this technology will be used in conjunction with optical mapping by employing multiple fluorescent probes (i.e. voltage-sensitive, calcium-sensitive, NADH, etc.) to study intact excitation-contraction coupling in the heart, without the need for pharmacological inhibition of mechanical contraction. Mathematical image processing would allow for virtual immobilization of the heart surface and thus significant reduction or elimination of motion artifacts in surface optical recordings. The combination of optical mapping with structured light will allow for multi-modality imaging with high temporal and spatial resolution data. This data could be used to characterize major aspects of cardiac physiology measured simultaneously and free of motion artifacts, i.e. excitation, calcium signaling, mechanical contraction, and metabolism. Presently, these normally intertwined phenomena are typically studied in isolation from each other.

From a clinical perspective, structured light imaging could greatly aid in mechanical assessment of specific diseases during open-heart surgeries or in the use of percutaneous transvenous optical light-guide catheters. This technology would allow for mapping of tissue strain and 3-D endocardial and/or epicardial mechanics in patients with cardiomyopathy at high temporal and spatial resolution. In combination with novel near-infrared dyes, this technology could provide the basis for future clinical applications of various molecular optical probes by solving the problem of motion “artifacts” in a beating human heart. Such future structured-optical imaging will significantly improve spatial resolution of clinical electrophysiology studies that are required for future high resolution ablation therapy, tissue engineering, and gene therapy.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.

Structured light reconstruction from a beating rabbit heart. A: Texture map with cardiac cycle overlaid from apex (red) and left ventricle (green). B: Mesh produced by three phase-shifted fringe images. The color-map depicts the z-coordinate of the epicardial surface. C: Interpolated mesh with cardiac cycles in 3-D perspective. D: Texture map and interpolated mesh with cardiac cycles in 3-D perspective. E: Slice removed from structured light model to reveal the 3-D surface contour of the heart.