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DETECTION OF CARDIAC CYCLE FROM INTRACORONARY ULTRASOUND

DONGBAI GUO* and PETER RICHARDSON†
*Oracle USA, Nashua, NH; and †Engineering Division, Brown University, Providence, RI, USA

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Abstract—In this paper, we describe a method automatically to determine the phase of a cardiac cycle for each video frame of an intravascular ultrasound (IVUS) video recorded *in vivo*. We first review the principle of IVUS video and demonstrate the general applicability of our method. We show that the pulsating heart leads to phasic changes in image content of an IVUS video. With an image processing method, we can reverse this process and reliably extract the heart-beat phase directly from IVUS video. With the phase information, we demonstrate that we can build 3-D (3D) time-variant shapes and measure lumen volume changes within a cardiac cycle. We may also measure the changes of IVUS imaging probe off-center vector within a cardiac cycle, which serves as an indicator of vessel center-line curvature. The cardiac cycle extraction algorithm requires one scan of the IVUS video frames and takes *O*(*n*) time to complete, n being the total number of the video frames. The advantage of this method is that it requires no user interaction and no hardware set-up and can be applied to coronary scans of live beating hearts. The extracted heart-beat rate, compared with clinical recordings, has less than 1% error. (E-mail: dbguo@ieee.org)   © 2006 World Federation for Ultrasound in Medicine & Biology.

Key Words: **Intracoronary ultrasound, Image processing, Cardiac cycle detection, Shape reconstruction, Measurement.**

INTRODUCTION

Intracoronary ultrasound

Heart and coronary artery diseases are the largest cause of death in western societies (Phibbs et al. 1971). Intravascular ultrasound (IVUS) is one of the most important imaging modalities for diagnosing coronary vascular deceases. Typically, the spatial and temporal resolution of IVUS is much higher than those of other imaging modalities, allowing it to image the shape, composition, and movement of the blood vessel wall.

IVUS has widespread clinical uses. Examples include the assessment of luminal and plaque morphology (Escaned et al. 1996), assessment of atherosclerosis (Honye et al. 1992), interventional guidance (Kimura et al. 1992; Nissen et al. 1991; Rosenfield et al. 1992; Fitzgerald and Yock 1993), and tissue classification (Tobis et al. 1991; Lee et al. 1992; Fitzgerald et al. 1992). It is also important for mathematical modeling of blood vessel mechanics, for example, using IVUS-based vessel models to explain/predict plaque rupture (Richardson et al. 1989; Loree et al. 1992; Lee et al. 1992; Cheng et al. 1993) and collapse of stenotic arteries (Aoki and Ku 1993).

Address correspondence to: Dongbai Guo, OracleUSA, NEDC, Nashua, NH 03062, USA. E-mail: dbguo@ieee.org

Motivations for cardiac cycle detection

In this paper, we introduce a method to derive the phase in the cardiac cycle from IVUS video alone. Although many IVUS-based applications have been developed, most of them concentrate on extracting the morphologic features of a blood vessel, not its dynamics. IVUS has the advantage of recording the motion of a blood vessel in response to arterial pressure change.

Because vessel mechanical properties are determined by the tissue composition, discovering the dynamics of a blood vessel, in addition to its morphologic feature, will significantly improve diagnostic benefits of IVUS. A critical step in studying the dynamics is to determine the phase in the cardiac cycle for each frame of an IVUS video. With phase information through a succession of heart-beats, we may reconstruct the shape of a blood vessel for a particular phase in the cardiac cycle. From these reconstructions of the response of a vessel segment to the arterial pressure change, one may estimate its mechanical properties (Lee et al. 1992).

Knowing the phase in the cardiac cycle for each video frame also enables the removal of the jittering motion of cardiac ultrasound, thus benefiting IVUS applications (Nadkarni et al. 2003) such as tissue classification (Zhang et al. 1998), 3-D modeling (Klingensmith et al. 2003, 2000; Olszewski et al. 2000), and tissue mechanical property estimation (Cespedes et al. 2000; Cheng et al. 1993).

Previous work

Existing methods for determining the phase in the cardiac cycle are either to analyze the electrocardiogram (ECG) signal overlaid on top of IVUS images (Zhang et al. 1998) or to use ECG-gated IVUS video capturing (von Birgelen et al. 1997; Terashima et al. 1997; Klingensmith et al. 2000). The latter is automated and its process is the following (von Birgelen et al. 1997). A computer is connected to a custom-built step motor, an ECG device and a frame grabber receiving video feed from the IVUS imaging station. The computer may send triggering signals to either the step motor or the frame grabber. The triggering signals drive the step motor that pulls the IVUS imaging catheter forward. To capture an IVUS field at a new location, the computer monitors the ECG input until it positively detects the second peak of an R-wave. At this moment, it sends a second signal to the frame grabber to capture an IVUS image. The process continues to the next capturing position and so on. When the vessel curvature is ignored, one may assemble all the images and create a shape corresponding to the peak of the R-wave.

Our approach

In this paper, we present a method to determine the cardiac cycle of a video frame automatically from an IVUS video. To accomplish this, we first study the motion of the IVUS imaging probe and the coronary artery, and conclude that the motion as observed by an IVUS imaging probe is dominated by the transient motion driven by the heart-beat. This leads to phasic variation in image content of an IVUS video, and this change has the same frequency as the heart-beat. With image processing techniques, we can extract the cardiac cycle directly from IVUS video. The method described in this paper is based on the first author's PhD thesis (Guo, 2000).

Because our method can be directly applied to *in vivo* IVUS recordings and reconstructs time-variant shape series, we are not limited to static dimension measurement and can make important quantitative measurements of the dynamics of the vessel wall. Such measurements make possible important studies such as tissue mechanical responses (de Korte et al. 1998) and thus take the full advantage of IVUS imaging.

When compared with the ECG-gated method (von Birgelen et al. 1997; Terashima et al. 1997; Klingensmith et al. 2000), this method has the advantage of directly building 3-D models solely from IVUS. There is no need for any set-up process or custom-built hardware and thus it is easier to use in a clinical environment. It can be applied to archival videos as well. Second, our method operates in a continuous fashion. We can extract pulsatile shapes instead of a single shape for each IVUS run, thus making phase-correlated measurement feasible. Next, our capture process does not have the step-pulse-capture style of motion; therefore, it has less than half the capture time of the ECG-gated method for the same axial resolution of a 3-D reconstruction. Finally, both external ECG gating and overlaid display of ECG signal with ultrasound can suffer from systematic errors. A recent study (Walker et al. 2002) shows that as much as a 90-ms (equivalent to three IVUS video frames) delay can exist between IVUS and the ECG signal. Our work, however, uses the intrinsic motion to recover the cardiac cycle and therefore does not have this type of system error. We are in the process of studying such error for ECG-gated IVUS video capture.

Another related image-based method (de Winter et al. 2004) uses a user-selected heart rate to derive a series of end-systolic images from an IVUS video. Our work differs from this method in that we compute a time-variant heart rate from an IVUS video, rather than taking a constant input value.

A limitation of our method is that we ignore viscoelastic effects in the coronary artery wall and assume that the maximum lumen area occurs at peak systolic pressure. This is, however, a common assumption made in computational studies because of the lack of data for artery viscoelastic properties (Cheng et al. 1993).

Organization of this paper

In the protocol section below, we discuss the experimental set-up and preprocessing of an IVUS video. In the analysis section, we study the principle of IVUS video and describe the general applicability of our method. We then describe our algorithm for the automatic extraction of the heart cycle from IVUS video frames. In the application section, we show some applications of our method, for 3-D time-variant shape reconstruction, phase-correlated volume, and motion measurements.

IVUS VIDEO CAPTURING AND PREPROCESSING

All the procedures were performed according to the guidelines of Dartmouth College Animal Research Committee and the National Institutes of Health. In an epicardial IVUS operation, an imaging catheter is inserted, over a guide wire, to an artery on the surface of the heart. At the tip of the imaging catheter is the imaging probe, an ultrasound transducer, which can emit and receive ultrasound waves in a pulse-echo mode. The acoustic response of the surrounding tissues is converted into radio-frequency (RF) signals by the transducer. The IVUS imaging station digitizes the RF signals and scan-converts them into video frames. Typically, an imaging