Cardiovascular Informatics

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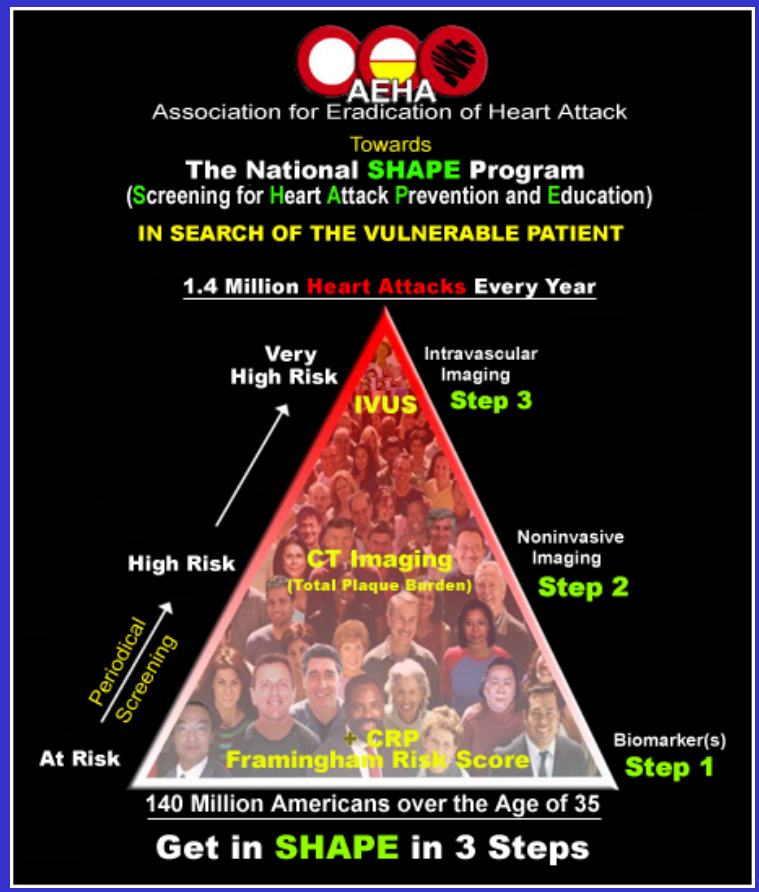
What is the leading cause of death in the United States since the beginning of the 20th century?
Except for one year (1924)!

Fatal Heart Attack!

Coronary Heart Disease Statistics (Source: American Heart Assoc.)

1. Coronary heart disease is the leading cause of death in Western nations, claiming approximately 446,000 lives in the United States annually
2. 12.9 million people have CHD in the U.S.
3. Approximately 1.2 million new cases will be diagnosed this year
4. Annually 1.4 million Americans will have a heart attack
5. 50% to 60% of first heart attacks will be fatal
6. 85% of sudden heart attacks may be prevented if the conditions that lead to the attack are diagnosed early enough to prescribe treatment
7. Quantitative methods will increase our understanding



Cardiovascular Informatics (2)

Mission: To develop the theoretical framework and computational tools to aid physicians in scoring patient vulnerability and the likelihood of a future coronary event.

Objectives: The development of Comprehensive Semi-Automated systems that will aid in the analysis of risk assessment for vulnerable patients via:

-CT

-MRI

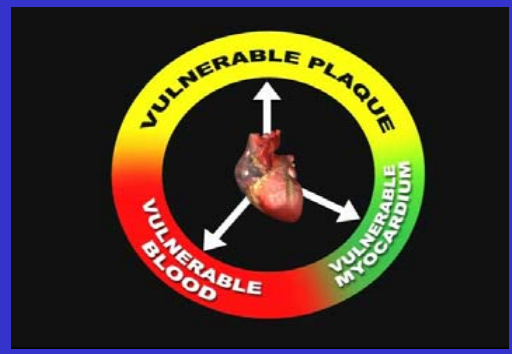
-Cath-Lab

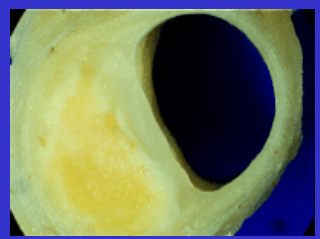
What is vulnerable plaque?

Dangerous forms of fat buildup (atherosclerotic plaques) in the arterial wall that can rupture or induce thrombosis and lead to critical disruption of blood flow.

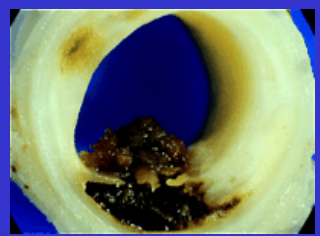
Challenges:

- Shape Modeling
- Shape Estimation
- Motion Estimation
- Segmentation of Plaque

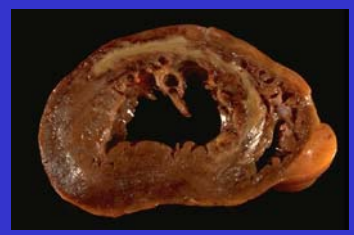




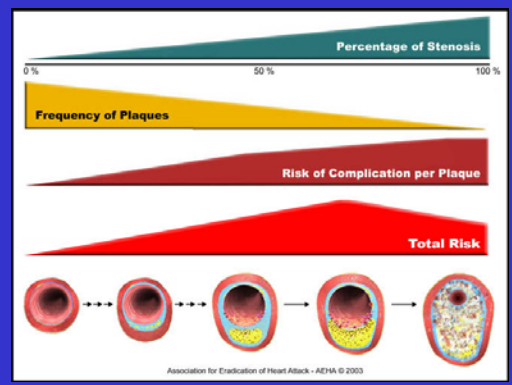
Vulnerable Plaque



Ruptured Plaque



Myocardium



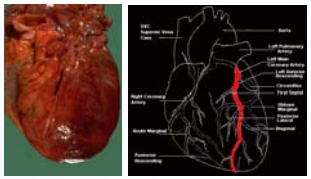
***Circulation.* 2003;108:1664**

Analysis of the Coronary Arteries

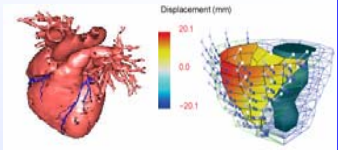
Objective: Shape-motion analysis of the coronary arteries.

Challenges

- **Morphology:** Coronary arteries are dynamic curvilinear structures with a great degree of variability and tortuosity



- **Motion:** Complexity of the non-rigid motion of the left ventricle and lack of reference landmarks



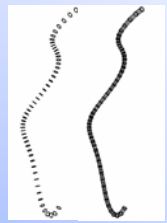
Materials

- All studies were performed using an Imatron Electron Beam Computed Tomography scanner in 3 asymptomatic volunteers and also on synthetic data.
- Voxel resolution 0.5x0.5x1.5 mm, 5 phases of the beating heart, ordered from the end-systolic (ES) phase to the end-diastolic (ED) phase.

Modeling

1. LAD shape model

- Parametric curved axis with Frenet-Serret frame
- Cross sectional plane – orientation



$$\begin{pmatrix} c_1(u) \\ c_2(u) \\ c_3(u) \end{pmatrix} = \begin{pmatrix} Px_1 & Px_2 & Px_3 & Px_4 \\ Py_1 & Py_2 & Py_3 & Py_4 \\ Pz_1 & Pz_2 & Pz_3 & Pz_4 \end{pmatrix} \begin{pmatrix} u^3 \\ u^2 \\ u \\ 1 \end{pmatrix}$$

$$Tangent\ t(u) = \frac{\vec{c}'(u)}{|\vec{c}'(u)|}$$

$$Binormal\ b(u) = \frac{\vec{c}'(u) \times \vec{c}''(u)}{|\vec{c}'(u) \times \vec{c}''(u)|}$$

$$Normal\ n(u) = b(u) \times t(u)$$

$$\begin{bmatrix} a_1(u,v) \\ a_2(u,v) \\ a_3(u,v) \end{bmatrix} = r(u) \begin{bmatrix} N_1(u) & B_1(u) \\ N_2(u) & B_2(u) \\ N_3(u) & B_3(u) \end{bmatrix} \begin{bmatrix} cos(v) \\ sin(v) \end{bmatrix}$$

2. Heart-centered coordinate system

Define local coordinate system with reference to long axis of the heart

3. LAD dynamics:

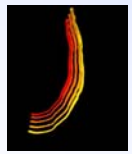
Shape-motion parameters are expressed by defining a local coordinate system for the human heart. LAD motion is expressed as a composition of three motion primitives:

1) LAD longitudinal expansion

$$\vec{T}_{LL}(u,t) = [1, 1, c^t(u,t)]^\top$$

2) LAD radial displacement

(measured from the long axis of the heart)



$$\vec{T}_{RD}(u,t) = [c_1^t(u,t), c_2^t(u,t), 1]^\top$$

3) LAD twist

(with respect to the normalized heart's coordinate system)

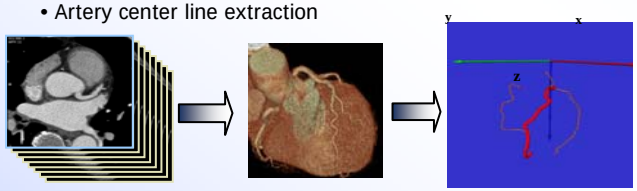
$$\vec{T}_T(u,t) = \begin{bmatrix} cos(c^t(u,t)) & -sin(c^t(u,t)) & 0 \\ sin(c^t(u,t)) & cos(c^t(u,t)) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\vec{m}(u,v,t) = \vec{T}_T(u,t) \cdot (\vec{T}_{RD}(u,t) \cdot (\vec{T}_{LL}(u,t) \cdot (s(u,v,t-1))))^\top$$

Analysis

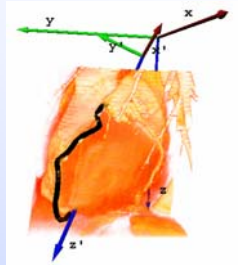
1. LAD segmentation

- Registration of coronary artery template
- Artery center line extraction



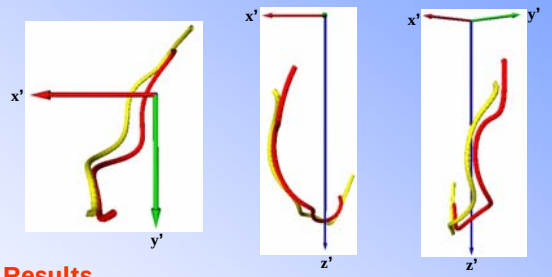
2. Estimation of heart-centered coordinate system

Transformation w.r.t. the base and apex of the heart



3. Fitting of a deformable model to the LAD

- Parametric shape-motion model
- Global and local deformations



Results

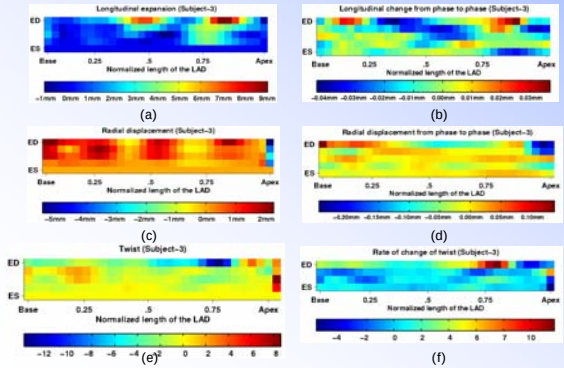
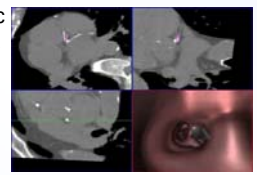


Figure 1: Estimated shape-motion parameters for Subject-3 from ES to ED, (a) Longitudinal expansion, (b) rate of change of longitudinal expansion, (c) radial displacement, (d) rate of change of radial displacement (e) twist, and (f) rate of change of twist.

Discussion & Conclusion

- Results from simulated data and from three asymptomatic subjects agree with expected physiological trends.
- Model provides a clinically relevant and anatomically normalized reference frame, which allows between-subject comparison.

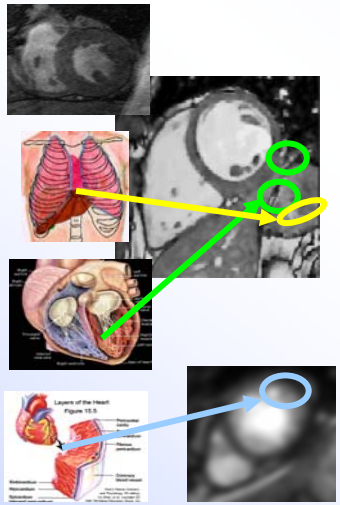


Cardiac Function Descriptors

Objective: Fully automatic delineation of the left ventricle (LV) muscle for the computation of critical cardiac function descriptors (e.g., ejection fraction and wall thickening).

Challenges

- Fuzzy nature of the MRI due to cardiac dynamics and flow artifacts
- Low myocardium to liver tissue contrast
- Papillary muscles attached to myocardium
- Partial voluming due to trabeculae carneae



Materials and Methods: All experiments were performed on a Philips GYROSCAN NT Intera scanner at 1.5 T using VCG gating in 8 asymptomatic volunteers and 12 symptomatic subjects.

MRI Acquisition: Contiguous 10 mm short axis slices of the entire LV were obtained using Cine bFFE sequence: TE/TR/flip: 1.6/3.2/55 deg; 38-40 msec temporal resolution.

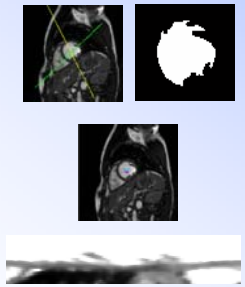
Data Analysis: The data was exported to a stand-alone workstation for automatic myocardial segmentation. For validation purposes the myocardium was circumscribed manually by two experts, on a commercially available Philips EasyVision post-processing workstation.

Automatic Segmentation: Our main contributions are the following: 1) automatic localization of the LV and myocardium using multi-view, intensity, and shape information; 2) hierarchical multi-class multi-feature fuzzy connectedness algorithm to overcome the low contrast between interfacing tissues; and 3) integration of shape-oriented transforms, myocardial fuzzy affinity, and optimal path computation using dynamic programming to overcome anatomy specific challenges.

Algorithm

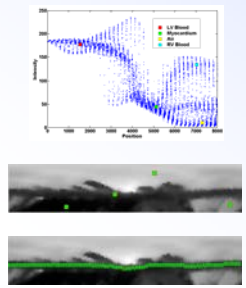
1. Automatic LV Localization

- Transform the scout images onto short axis slices
- Intensity and morphology-based LV centroid estimation
- Morphology-based myocardial region estimation



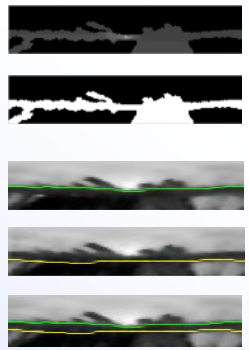
2. Automatic Myocardial Region Segmentation

- Use the sample statistics and the centroid for the hierarchical multi-class multi-feature fuzzy affinity-based myocardium segmentation



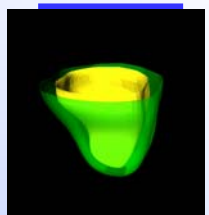
3. Automatic Myocardial Contour Detection

- Find the optimal path for myocardial contours in polar coordinates using dynamic programming
- Cost function consists of myocardial affinity, gradient, and spatial continuity



4. Fitting a 3D Elastically Adaptive Deformable Model

- Fit a 3D elastically adaptive physics-based deformable model to obtain 3D spatial continuity



Results

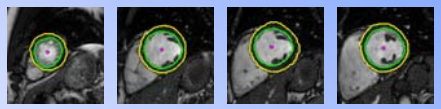


Figure 1: Segmented end-diastolic myocardium.

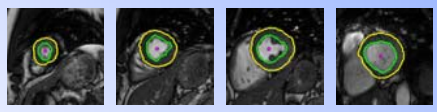


Figure 2: Segmented end-systolic myocardium.

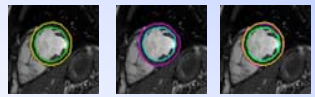


Figure 3: Myocardial contour tracings overlaid on the original image a) automatic, b) manual, and c) both.

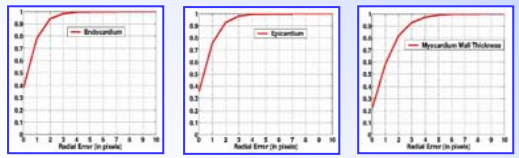


Figure 4: Cumulative distribution of radial distance error for endocardium, epicardium, and wall thickness.

Discussion

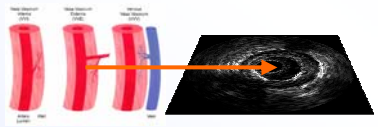
- The proposed method does not require any user interaction.
- The boundary tracings by our method are consistent with the manual tracings of the clinical experts.
- The method allows computation of cardiac parameters such as end-diastolic and end-systolic volumes, stroke volume, ejection fraction, cardiac output, wall thickness, and wall thickening.
- The method exhibits an error of 3 or more pixels for endo- and epicardial contours and 5 pixels for wall thickness in less than 1% of the cases.

Intravascular Ultrasound-Based Imaging of Vasa Vasorum for Detection of Inflammation and Vulnerable Plaque

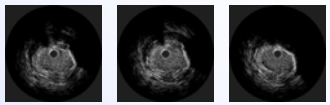
Objective: Imaging of vasa vasorum (VV) microvessels using microbubble-contrast enhanced IVUS images and quantification of plaque perfusion.

Challenges

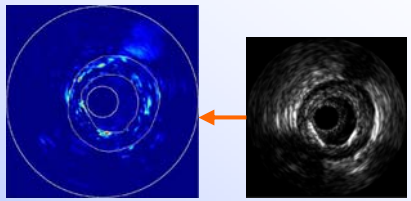
- Ultrasound "speckle noise"



- Cardiac motion



- Subtle nature of perfusion-induced enhancement



Materials and Methods: Images were acquired using the DICOM standard at either 10 or 30 frames/s. Our analysis was run on a Pentium-IV based 2GHz PC. IVUS baseline images were recorded for a period of 30 s to 1 min, after which contrast agent was injected and a contrast-enhanced sequence recorded for a similar period of time. In-depth analysis was performed on 7 at-risk patients.

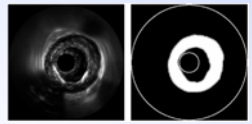
Contributions:

1. Novel contrast-based imaging
2. Motion compensation by automated determination of cardiac phase for each frame in the IVUS sequence
3. Differential image analysis for enhancement detection

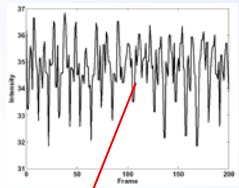
Algorithm

1. Automatic Determination of Cardiac Phase Using IVUS Image Sequence

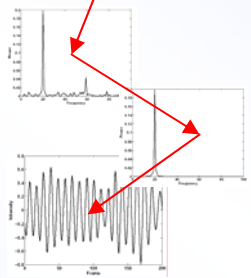
- Operator selects region-of-interest (ROI) in single IVUS frame



- Mean intensity or mean inter-frame intensity difference tracked over time

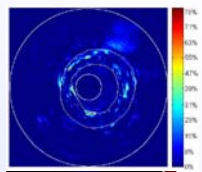


- Frequency-domain signal filtering
- Peaks in reconstructed time-domain signal correspond to same point in cardiac phase; frames extracted from these points will be phase-correlated

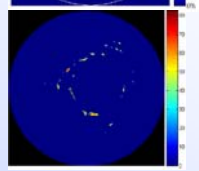


2. Difference-Image Analysis for Detection of Perfusion in Vasa Vasorum

- Difference images produced by subtracting baseline and post-contrast injection frames; frame averaging used for noise reduction



- Thresholded using statistical techniques: Bayesian analysis of grey-level statistics followed by Markov modeling to decrease false positives and enhance borders of coherent regions of enhancement.



Results

Case 1: 1,073-frame IVUS sequence acquired over approximately 2 minutes (10 frames/s)

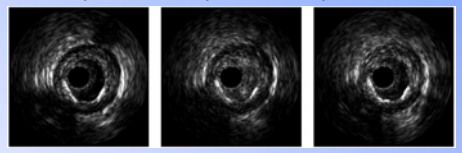


Figure 1: Raw IVUS images; pre-, during- and post-injection for a single case

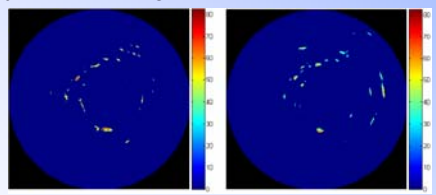


Figure 2: Thresholded difference images depicting enhancement in plaque area

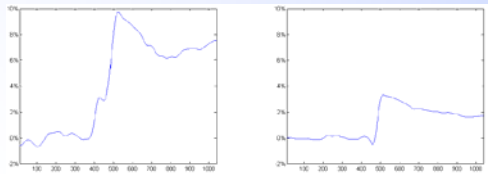


Figure 3: Enhancement over time in the (a) plaque and (b) adventitial areas. Sharp peak indicates point of contrast injection.

Discussion

- There is a growing body of evidence that vasa vasorum (VV) is a strong marker of plaque inflammation and vulnerability.
- IVUS is the most powerful and widely-available technology in the field of cardiology; however, the major drawback of IVUS has been its lack of ability to provide information on plaque activity and inflammation.
- Research towards detection of VV using IVUS will help remove this limitation and allow improved vulnerable-patient screening.