Cardiac Imaging Modalities

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Introduction

• Coronary heart disease: the vessels that supply oxygen-carrying blood to the heart, become narrowed and unable to carry a normal amount of blood
  → the heart does not receive sufficient oxygen
  → heart attack and death
• Coronary heart disease is the leading cause of death in the United States, responsible for nearly 460,000 deaths each year
• Cardiac imaging → more accurate diagnostics

Overview

Cardiac imaging modalities:
1. Magnetic Resonance Imaging (MRI)
2. Magnetic Resonance (MR) velocity mapping
3. Computed Tomography (CT)
4. Ultrasound (US) imaging
5. Doppler echocardiography
6. Tissue Doppler Imaging (TDI)

MRI

• Developed in the early 1970’s
• Fundamental quantum mechanical property of proton: spin
• Protons precess around an internal axis of rotation: magnetic moment
• Magnetic field (bar magnet)

MRI (Continued)

• No external magnetic field: random orientation of μ
• MRI: huge static magnetic field B is applied (1.5T)
• μ align protons
• Two configurations: μ parallel to the direction of B
  → protons precess coherently
• The frequency of precession is proportional to the amplitude of B
• A radiofrequency field is directed to the heart

MRI (Continued)

• Magnetic field gradients: spatial information
• Linear variation of B in all three dimensions
  → precessional frequencies of protons are linearly dependant upon their spatial location
• Measure of the frequency and the phase of the precessing protons: digitization of this induced voltage
• Inverse 2D Fourier transform: conversion into the spatial domain
  → image
MRI (Continued)

- Full 3D capabilities
- Excellent soft-tissue contrast
- Application different configurations:
  - high spatial resolution: 0.5 - 1.5mm
  - acquisition time: real time - 13s
  - slice thickness: 1.5 - 8mm
- Tradeoff: high spatial resolution/short acquisition time

MRI (Continued)

- Two main configurations: Spin-echo and Gradient-echo
  - Spin-echo entire change in magnetization used to create the image
    - high spatial resolution (0.5mm)
    - very slow (13s for one slice)
  - Gradient-echo only a part of the change in magnetization used to create the image
    - lower spatial resolution (1mm)
    - very fast (2s, real time)

MRI (Continued)

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MRI (Continued)

- Standard reference cardiac anatomy:
  - Spin-echo technique: representation of cardiac and thoracic anatomy in black blood imaging (blood signal suppressed)
  - LV= Left Ventricle, LA=Left Atrium, Ao=Aorta
  - Spatial resolution: 0.7x0.7mm Acquisition time: 12 seconds
  - Method of choice to detect primary tumors of the heart

MRI (Continued)

- Assessment of the heart function:
  - Gold standard measure of the cardiac output (amount of blood pumped out by each ventricle in one minute)
  - Gradient-echo technique:
    - movie series of the heart chambers in 3D
    - better quantification of the heart chambers volumes

MRI (Continued)

- State-of-the-art technique
- Allows more accurate diagnostics
- Very expensive (in the order of $1.5 million)
- For long acquisition times:
  - artifacts due to respiratory movements
  - can require a short breath hold

MR velocity mapping

- Particular use of MRI
- In B, spins of protons are precessing at a frequency dependent on the strength of the field
- Magnetic field gradient applied
- If the protons move, change in the frequency of the precession
- Frequency shift proportional to the velocity of the moving particle
MR velocity mapping (Continued)

- Magnetic field gradient applied in each direction
  - velocity in different directions
- Four images: 3 velocity-encoding ones
  - 1 reference image
- Subtraction of the reference image to the 3 velocity-encoding ones:
  - stationary tissue: phase shift = 0
  - moving tissue: phase shift ≠ 0
- Phase different map: proportional to the velocities

Applications:
- Velocity mapping of the heart wall
- Blood-flow measurements

Ex:
Aortic valve prevents backflow from the aorta into the left ventricle
- mapping of blood velocity distribution downstream (below) of aortic valve prostheses
- visualization of regurgitation (abnormal backflow of blood in the aorta)

MR velocity mapping (Continued)

Mapping of blood velocity distribution downstream of aortic valve prostheses (typical case):
- Spatial resolution: 1mm x 1mm
- Section thickness: 5mm
- Acquisition time: 8 seconds per image

Color-encoded axial flow velocity images measured downstream of the valve in five consecutive heart phases (30ms). Values are in centimeters per second.

Computed Tomography (CT)

- CT invented in the early 1970’s
- Refined version of X-ray machines:
  - X-ray from a source pass through the patient and are detected by a film on the opposite side of the body
  - CT: the source and detectors rotate together around the patient
  - 1D projections at a number of different angles
  - view of a specific level of the body (slice)
  - Sensors: amount of X-rays absorbed by tissues
  - Differential attenuation of X-rays in the body
  - contrast (X-ray attenuation is efficient in bone)

CT (Continued)

- High spatial resolution: 1mm
- Slice thickness: 1.25mm
- Acquisition time: 20s
- Reasonable contrast between soft tissues
- Recent developments:
  - spiral CT
  - multislice CT (MSCT) acquisition of 3D images

Spiral CT:
- Conventional CT: only a single slice can be acquired at one time
- If multiple slices required, patient table is moved time delay between each image
- + spatial misregistration between slices
- Spiral CT: trajectory of the X-ray beam is a spiral
- A full 3D image can be acquired shortly
Multislice spiral CT (MSCT):  
- Improvement of spiral CT  
- Incorporation of an array of detectors in the direction of the table motion  
- Visualization of larger volumes in a given time  
- Visualization of a given volume in a shorter scan time  
- Rotation time: 0.5s  
- High spatial resolution: 0.5x0.5x0.5mm  
- The whole heart (15x15x15cm) can be covered within a single breath hold of 18s  
- 4, 8, 16 slices detectors  
- Slice thickness: 1.25 - 5 mm

Applications:  
- Visualization of coronary arteries  
- High resolution assessment of morphological detail of the heart’s chambers (including the cardiac valves)  
- Accurate measurement of functional parameters of the heart such as wall thickening, diastolic and systolic volumes

Example:

Texas Heart Institute (2003)

The two spiral CT views above show that the left coronary artery (red arrows) which supplies functional blood to the heart is normal.

Example:

Texas Heart Institute (2003)

This 3D spiral CT view (volumetric reconstructed image) is looking down on top of the left ventricle. It shows a normal coronary artery (black arrow).

CT (Continued)

- State-of-the-art technology  
- Very expensive ($2 millions for the latest models)  
- High spatial resolution  
- Good overall image quality of the entire heart but possibility of artifacts in the data  
- Major drawback: generates ionizing radiations  
  - tissue damage  
  - limit on the total dose per year  
  (1000 planar chest X-rays, 15 head CTs, or 5 full-body CTs)

Ultrasound (US) imaging

- Ultrasound introduced to the medical world in the 1960's  
- Piezo-electric crystal (transducer):  
  - placed against the skin of the patient near the region of interest (heart)  
  - stream of high frequencies sound waves (1-10MHz) which penetrate into the body (c=1540 m/s)  
  - detects sound waves as they echo back from the internal structures of the organs  
- Different tissues reflect those sound waves differently:  
  - signature measured and transformed into an image in real time  
- For the study of the heart: called echocardiography
Ultrasound imaging (Continued)

Interaction between US beam and Tissue
- At an interface, there is:
  - reflection
  - refraction and transmission
- During the propagation of the beam in a medium, there is:
  - absorption: \( I(x) = I_0 e^{-\mu x} \)
  - \( \mu \) = attenuation coefficient
  - \( \mu \) is a function of the frequency of the beam, it increases when the frequency increases

Ultrasound imaging (Continued)

Two configurations:
- Continuous wave US
- Pulsed US
  - Most common
  - Pulse duration: 1 \( \mu \)s
  - Pulse rate: 1000 pulses/s

Ultrasound imaging (Continued)

Applications:
- Visualization of most valve diseases (stenosis or regurgitation)
- Detection of ischaemic heart disease (ischaemia results in regional defects in myocardial contraction and mass. An injured myocardium is unable to thicken during systole.
- Visualization of primary heart tumors
- Characterization of pericardial effusion which is an abnormal collection of fluid inside the pericardial (the sac that covers the heart)

Example:
The Echocardiography Laboratory of the University of Medicine and Dentistry of New Jersey (2000)

Pericardial effusion = abnormal collection of fluid inside the pericardial

Ultrasound imaging (Continued)

- The easiest, most easily portable and cheapest cardiac imaging modality
- Harmless
- Provides real time images of regions of the heart
- High resolution
- Improvements - 3D images
  - Doppler echocardiography
  - Doppler Tissue Imaging
Doppler echocardiography

- Particular use of echocardiography
- Doppler shift: change in frequency of received signal is related to the velocity of reflecting structure (blood vessel for example):

\[
\Delta f = \frac{(2f_0 \cos(\theta) v)}{c}
\]

- Provides measurements of the velocity of the reflecting structure

Doppler echocardiography (Continued)

Several types of Doppler imaging:
- Continuous Doppler (continuous wave)
- Pulsed Doppler (pulsed US)
- Color Doppler imaging

Doppler echocardiography (Continued)

Applications:
- Most common technique used for the detection and evaluation of severity of valvular regurgitation
- Characterization of aortic stenosis
- Aneurysms
- Pericardial effusion

Tissue Doppler Imaging (TDI)

- Variation of conventional color Doppler imaging
- Doppler shifts obtained from myocardial tissue motion compared to red blood cells:
  - higher amplitude (40 dB higher)
  - move about 10 times slower (0.06 to 0.24 m/s)
- thresholding + filtering that rejects the echoes originating from blood pool
- velocity measurement of the myocardial tissue
- Velocity data superimposed on the gray-scale image

TDI (Continued)

Applications:
- Velocity of contraction and relaxation of a specific piece of myocardium can be examined
- Both systolic and diastolic function can be determined by measuring the movement of the myocardium
- Myocardial ischaemia affects regional contraction and relaxation. These alterations can be quantified by tissue velocity imaging. Indeed it has been observed that ischaemia results in rapid reduction of systolic velocities and early diastolic velocities
TDI (Continued)

Example: J. Attard, D. Condon (2001)

During systole (left), the walls of the LV move towards the apex (coded in red), while during diastole (right), they move up towards the base (coded in blue).

Conclusion

- US: real time, cheap, easily portable, harmless but not very good contrast in some applications
- MRI: high resolution, very good contrast, but expensive
- CT: high resolution, fast but expensive and generates ionizing radiations
- Development of techniques:
  - TDI
  - MR velocity mapping
- MRI can detect heart attack in emergency room patients with chest pain more accurately and faster than traditional methods
- Reduction of the costs of CT and MRI scanners

References

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