MEDICAL IMAGE COMPUTING (CAP 5516)

LECTURE 3 & 4: Medical Imaging Modalities

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Medical Image Analysis

• Because of the rapid technical advances in medical imaging technology and the introduction of new clinical applications, medical image analysis has become a highly active research field.
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- Medical images are often multidimensional (2D, 3D, 4D,nD), have a large dynamic range, are produced on different imaging modalities in the hospital, and make high demands upon the software for visualization and human–computer interaction.
  - A high resolution MR image of the brain, for instance, may consist of more than 200 slices of 512 x 512 pixels each, i.e., more than 50 million voxels in total. (100MB)
  - In clinical studies that involve the analysis of time sequences or multiple scans of many subjects, the amount of data to be processed can easily exceed 10 GB.
  - While 8 bits or 1 byte per pixel is usually sufficient in digital photography, most medical images need 12 bits per pixel (represented by 2 bytes in the computer memory).
Medical Image Analysis - Manual

• Often accepted as surrogate of the truth (if biopsy or real ground truth is not available)
• However, manual analysis is highly subjective because it relies on the observer’s perception.
  – Intra and inter-observer agreements/variabilities
• It is highly tedious
Observer Variability – Example: Liver lesion

Intra- (one week interval)
Medical Image Analysis-Automated

- Different strategies for image analysis exist. However, few of them are suited for medical applications.
Medical Image Analysis-Automated

- Different strategies for image analysis exist. However, few of them are suited for medical applications.
- The reason is that both the medical image data and the model or prototype (i.e., the a priori description of the features to be analyzed), are typically quite complex.
Digital Images

What computer sees!
**Digital Images**

- **Definition:** A digital image is defined by *integrating* and *sampling* continuous (analog) data in a spatial domain [Klette, 2014].
PIXELS are ATOMIC ELEMENTS of an image.
In late 1960s, terminology ‘pixel’ was introduced by a group of scientist at JPL in California!
Image Types

• A scalar image has integer values

\[ u \in \{0, 1, \ldots, 2^a - 1\} \]

- \( a \): level (bit)

**Ex.** If 8 bit (\( a=8 \)), image spans from 0 to 255
  0 black
  255 white

**Ex.** If 1 bit (\( a=1 \)), it is binary image, 0 and 1 only.
Image Types-Color

- Image has three channels (bands), each channel spans a-bit values.
- RGB, Hue-Saturation-Brightness
Brief Introduction to Imaging Modalities
ELECTROMAGNETIC SPECTRUM  (P. Suetens)
X-Ray Imaging / Radiography

• The first published medical image was a radiograph of the hand of Wilhelm Conrad Roentgen’s wife in 1895. *Nobel Prize in Physics 1901.*

routine diagnostic radiography (2D images): chest x-rays, fluoroscopy, mammography, motion tomography, angiography, …
X-Ray Imaging / Radiography

\[ D = \log\left(\frac{I_{in}}{I_{out}}\right) \]

- \( D \) = Optical density
- \( E \) = Exposure (\( I_{in}/I_{out} \))
- \( I_{in} \) = Incoming light intensity
- \( I_{out} \) = Outgoing light intensity
Linear part (useful!)

- Maximum slope of the curve is known as the gamma of the film.
- A larger slope implies a higher contrast at the cost of a smaller useful exposure range.
- In low and high density areas, contrast is low and little information available.
- In linear part, slope characterize contrast of the film. Max slope is known as Gamma of the film.

**Defn. Contrast:** is the intensity difference in adjacent regions of the image.
Basics Use of X-Rays

- Dental examinations
- Surgical markers prior to invasive procedures
- Mammography
- Orthopedic evaluations
- Chest examination (Tuberculosis)
- Age estimation (forensic, left hand)
Clinical Examples – X-Rays

- Wrist
- Pelvis
- Hand
- Forearm
- Elbow
How Radiologists Search Abnormal Patterns in Chest X-Rays?

Patterns belonging to Potentially Malignant Lesions

Patterns belonging to Potentially Benign Lesions
How Radiologists Search Abnormal Patterns in Chest X-Rays?

Radiologists often report the following:
- Size, dimension, volume
- Pattern description,
- Location,
- Interaction with Nearby structures,
- Intensity distribution
- Shape
- …

Difficulties:
- Noise
- vessels can be seen as small nodules
- radiologists may miss the pattern
- patterns may not be diagnostic
- CT often required for better diagnosis
- size estimation is done manually in 2D
- Shadowing
- total lung capacity computation
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Computer algorithms can solve/simplify these problems for improved healthcare
Another Example for X-ray Imaging

Benign

Malignant
Ultrasound Imaging

- US is defined as any sound wave above 20KHz

1794-Lazzaro Spallanzani - Physiologist
First to study US physics by deducing bats used to US to navigate by echolocation

1826-Jean Daniel Colladon - Physicist
Uses church bell (early transducer) under water to calculate speed of sound through water prove sound traveled faster through water than air.

1880-Pierre & Jacques Curie
Discover the Piezo-Electric Effect (ability of certain materials to generate an electric charge in response to applied mechanical stress.)
1942-Karl Dussik - Neurologist
First physician to use US for medical diagnosis

1948-George Ludwig - MD
First described the use of US to diagnose gallstones

1958-Ian Donald
Pioneers in OB-GYN
Principle of US Imaging

US equipment assumes that sound velocity is constant in the body.

### Table: Acoustic Impedance of Body Tissues

<table>
<thead>
<tr>
<th>Body tissue</th>
<th>Acoustic impedance ($10^6$ Rayls)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>0.0004</td>
</tr>
<tr>
<td>Lung</td>
<td>0.18</td>
</tr>
<tr>
<td>Fat</td>
<td>1.34</td>
</tr>
<tr>
<td>Liver</td>
<td>1.65</td>
</tr>
<tr>
<td>Blood</td>
<td>1.65</td>
</tr>
<tr>
<td>Kidney</td>
<td>1.63</td>
</tr>
<tr>
<td>Muscle</td>
<td>1.71</td>
</tr>
<tr>
<td>Bone</td>
<td>7.8</td>
</tr>
</tbody>
</table>
Features of US Imaging

- **Resolution:**
  - direction of pulse propagation, pulse width 1-2mm
  - direction of scanning: beam width 2-3mm
  - **low resolution** and low SNR in deep region

- Ability of **imaging soft tissue**
- Imaging in **real time**
- Doppler image
- Artefacts

Color flow mapping shows simultaneous amplitude (US) and velocity information (doppler)
Clinical Use of US Imaging
Clinical Use of US Imaging

Renal Artery Blood Flow

manual measurements? can computer help calculating all blood flow and identify automatically the abnormal regions? (See Next Lecture, afternoon)

stenosis is seen
eca: external carotid artery
cca: common carotid artery
ica: internal carotid artery
Clinical Use of US Imaging

Bone, fat, and physical length Measurements – unborn babies
(Image Credit: S. Rueda, Oxford Univ.)
Computed Tomography (CT)

Tomo: slice/level (Greek)
Graphe: draw
CT Imaging (continue)

C-arm

CT

~CAT Scan
(computerized Axial tomography)

Micro-CT
3D Nature of CT
3D View Terminology

A Sagittal
B Coronal
C Axial
3D Images

I: Image
I(x,y,z) denotes intensity value at pixel location x,y,z

Note also that whatever you see on the left is right part of the body!
Clinical Use of CT Imaging

• Standard imaging technique in many organs, particularly gold standard for lung imaging
• Fast
• Radiation exposure
• Often used in surgery rooms
• Show anatomy and pathology
• Intensity values are (more-or-less) fixed, read as HU (Hounsfield Unit)
CT Imaging Example: Tumor

2D manual measurement of tumor size (short and long axis of tumor)
CT Imaging Example: Lung

(A) Normal  (B) Emphysema  (C) Ground Glass Opacity
(D) Fibrosis  (E) Micronodules  (F) Consolidation
CT Imaging Example: Cardiac

how to calculate the amount of fluid?
Magnetic Resonance Imaging (MRI)

- 1882-Nichola Tesla
  - Discovered rotating magnetic field
- 1971-Paul Lauterbur  NOBEL PRIZE
  - First invented MRI
- Late 1970-Sir Peter Mansfield (Nottingham)  NOBEL PRIZE
  - Developed mathematical techniques to create clearer images and also in minutes rather than hours as Lauterbur did.

- CT is more widely used than MRI.
- MRI does not have ionizing-radiation.
- MRI has excellent soft tissue contrast, while CT is preferred for lung and bone imaging.
- CT is fast (few seconds), while MRI is slow (sparse MRI ~5-10 mins, abdomen or brain may take 30-40 mins).
**Brief History of MRI**

- **Uhlenbeck and Goudsmit - 1925**: discovered the concept of a spinning electron by angular momentum to the magnetic dipole moment.
- **Pauli and Darwin - 1927**: Electron spin in quantum mechanics was taken into a part to the NMR phenomena.
- **Rabi - 1937**: Observed Larmor Frequency and nuclear magnetic resonances.
- **Rabi - 1944**: Awarded the Nobel prize for his resonance method.
- **Parkard and Arnold - 1951**: Introduced chemical shift as a result of -OH hydrogen bonding-the solvent effect.
- **Overhauser - 1953**: Indicated the effects of electron spin populations to nuclear spin polarization.
- **Shoolery - 1961**: The first NMR spectrometer was commercially available.
- **Ernst - 1991**: Awarded the Nobel prize for his contributions to high resolution NMR.
- **Lauterbur and Mansfield - 2003**: Awarded the Nobel prize for their discoveries regarding magnetic resonance imaging.

**1921** - Stern and Gerlach: the first atomic beam instrument.

**1926** - Schrödinger and Heisenberg: included a new branch formulation for quantum theory.

**1936** - Gorter: attempted to design the first instrument and used resonance properties of nuclear spin in the presence of magnetic field. However, his experiment was not successful.

**1943** - Stern: Awarded the Nobel prize for his discovery of magnetic momentum of the proton.

**1945** - Purcell, Torey and Pound: Very first NMR experiment in a bulk material.

**1952** - Bloch and Purcell: Awarded the Nobel prize for their development of a new method for nuclear magnetic precision measurements and the subsequent discoveries.

**1957** - Lauterbur and Holm: The first $^{13}$C spectra was obtained.

**1971** - Jeener: The first two dimensional NMR experiment (COSY).

**2002** - Wüthrich: Awarded the Nobel prize for his development of three-dimensional structure of biological macromolecules in solution.
Nobel Prizes for MRI

• 1944: Rabi
  Physics (Measured magnetic moment of nucleus)

• 1952: Felix Bloch and Edward Mills Purcell
  Physics (Basic science of NMR phenomenon)

• 1991: Richard Ernst
  Chemistry (High-resolution pulsed FT-NMR)

• 2002: Kurt Wüthrich
  Chemistry (3D molecular structure in solution by NMR)

• 2003: Paul Lauterbur & Peter Mansfield
  Physiology or Medicine (MRI technology)
MRI Hardware Setup - Details
MRI Basics
MRI Basics

No magnetization
The Magnet

Magnets field strength:

- Imaging: 0.2T to 2.0T
- Spectroscopy: 2.0T to 7.0T

- Low field: 0.2 - 0.5T
- Intermediate: 0.5 - 1.5T
- High field: 1.5 - 4.0T
- Ultra high: > 4.0T

Earth’s magnetic field = 5×10⁻⁵ Tesla
MRI is considered ideally suited for soft tissue problems

*** MRI is to soft tissue as x-ray is to dense tissue (bone)***

- Diagnosing multiple sclerosis (MS)
- Diagnosing brain tumours
- Diagnosing spinal infections
- Visualizing torn ligaments in the wrist, knee and ankle
- Visualizing shoulder injuries
- Evaluating bone tumours, and herniated discs in the spine
- Diagnosing strokes in their earliest stages
Types of MRI

- **Proton Density**
- **T2-Weighted**
- **T1-Weighted**
Image contrast summary: TR, TE
Brain MRI
The brain of a volunteer is imaged using a 3-T (left) and 9.4-T (right) magnetic resonance imaging machine. Credit: Rolf Pohmann/Max-Planck-Institute for Biological Cybernetics (https://www.nature.com/articles/d41586-018-07182-7)
T1 Weighted Image

<table>
<thead>
<tr>
<th>T₁/s</th>
<th>R₁/s⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7</td>
<td>1.43</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>0.25</td>
</tr>
</tbody>
</table>

white matter     
grey matter      
CSF

SPGR, TR=14ms, TE=5ms, flip=20°
T2 Weighted Image

<table>
<thead>
<tr>
<th>T2/ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSF</td>
</tr>
<tr>
<td>grey matter</td>
</tr>
<tr>
<td>white matter</td>
</tr>
</tbody>
</table>

SE, TR=4000ms, TE=100ms

1.5T
Safety in MRI
Diffusion Tensor Imaging (DTI)

- MRI (sub-)modality
- measures random Brownian motion of water molecules.
- useful for **tumor characterization** (densely cellular tissues exhibit lower diffusion).
Diffusion Weighted Imaging (DWI)

Glioblastoma Tumor
Clinical Use: Example
Clinical Use: Example

Myocardial Infarction Detection
Clinical Use: Example

rectal tumor
Now, neuroscientists have charted an equivalent map of the brain’s outermost layer — the cerebral cortex — subdividing each hemisphere’s mountain- and valley-like folds into 180 separate parcels.
Functional MRI (fMRI)

• measures brain activity through oxygen concentration in the blood flow.
• relies on the fact that cerebral blood flow and neuronal activation are coupled.
• when area of the brain is active (in use), blood flow to that area also increases.

• which part/location of the brain is activated when reading?
• which part/location of the brain is activated when listening music?
• which part/location of the brain is activated when searching puzzle?
fMRI Settings

Active Regions
Nuclear Medicine Imaging – PET/SPECT

- **Scint**: Scintigraphy, two-dimensional images
- **PET**: Positron Emission Tomography
- **SPECT**: Single Photon Emission Tomography

![Graph showing PET and PET-CT Sites in the US](chart1)

<table>
<thead>
<tr>
<th>Year</th>
<th>Fixed PET</th>
<th>Fixed PET-CT</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>215</td>
<td>715</td>
</tr>
<tr>
<td>2011</td>
<td>120</td>
<td>1030</td>
</tr>
</tbody>
</table>

![Pie chart showing clinical PET and PET-CT studies in 2011](chart2)
Nuclear Medicine Imaging – PET/SPECT

1,650,000 Clinical PET and PET-CT Studies in 2010 (US Statistics)

- Diagnosis: 33%
- Staging: 19%
- Treatment Planning: 10%
- Therapy Followup: 38%
Basics of PET Imaging

- uses short-lived positron emitting isotopes (produced by collimators)
- two gamma rays are produced from the annihilation of each positron and can be detected by specialized gamma cameras
- resulting image show the distribution of isotopes
- an agent is used to bind into isotopes (glucose, …)

Late 1950s, David L. Kuhl concept of emission and transmission
molecular activity is measured.
PET/CT and MRI/PET (Hybrid Imaging)

**PET/CT**
- choice of modality for oncological applications (yet)

**MRI/PET**
- superior soft tissue contrast resolution
- minimized radiation
What to Measure in PET?

• **SUV** (standardized uptake value: voxel-wise or region-wise) (SUVpeak, SUVmax, SUV\textsubscript{lbm})

• Metabolic lesion/tumor volume (**MTV**)

• **Shape** information of (functional) lesion (spiculated vs focal)

• **Texture** information of lesion (heterogeneous vs homogeneous)

• **Number** and **distribution** of the lesions (focal, multi-focal)
Clinical Use of PET: Example
Clinical Use of PET: Example
Serial and Simultaneous MRI/PET

Past

Now!
# Shallow Comparison of Imaging Methods

<table>
<thead>
<tr>
<th></th>
<th>Chest</th>
<th>Abdomen</th>
<th>Head/Neck</th>
<th>Cardiovascular</th>
<th>Skeletal/muscular</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CT</strong></td>
<td>gold standard</td>
<td>Need contrast for excellency, widely used</td>
<td>Good for trauma</td>
<td>Gold standard</td>
<td>Gold standard</td>
</tr>
<tr>
<td><strong>US</strong></td>
<td>no use except heart or P.Effusion</td>
<td>Problems with gas</td>
<td>Poor</td>
<td>Poor</td>
<td>Elastography</td>
</tr>
<tr>
<td><strong>Nuclear</strong></td>
<td>Extensive use in heart and therapy in lung</td>
<td>CT or MRI is merged</td>
<td>PET</td>
<td>Perfusion</td>
<td>bone marrow</td>
</tr>
<tr>
<td><strong>MRI</strong></td>
<td>growing cardiac applications</td>
<td>Increased role of MRI</td>
<td>Gold standard</td>
<td>Will replace ct in near future</td>
<td>Excellent</td>
</tr>
</tbody>
</table>
Summary

• Medical image analysis/computing is a highly active research field.
• Measurement is the key in MIC! Volumetry, morphometry, quantification, visualization are all necessary methods in diagnostic radiology applications.
• Different imaging modalities are in use for different clinical purpose(s)
• Imaging modalities have distinct properties from each other
References and Slide Credits

• **P. Suetens**, Fundamentals of Medical Imaging, Cambridge Univ. Press.
• ITK.org
• siemens.com
• slicer.org
• Must watch lecture (basic): https://www.youtube.com/watch?v=jWRIKNeCXjI
Questions?