Topic 1: Bio-Medical Imaging
Part I

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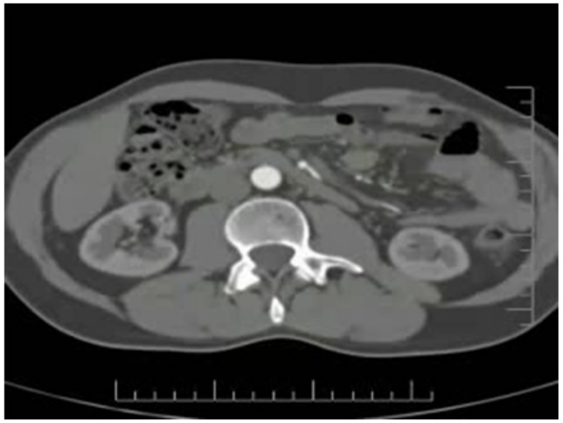
Medical Imaging

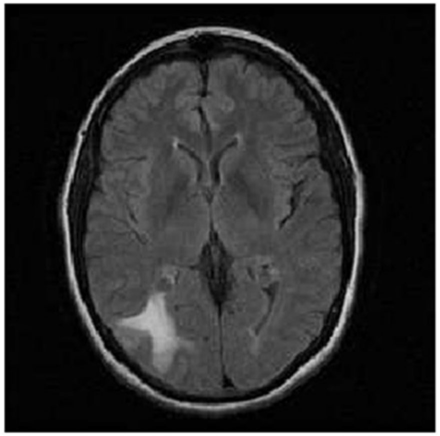
- Medical imaging refers to the techniques and processes used to create images of the human body (or parts thereof) for clinical purposes or medical science.



CT: abdominal part

- In the clinical context, medical imaging is also called radiology or "clinical imaging".

- Medical imaging techniques:
  – Computed Tomography (CT)
  – Magnetic Resonance Imaging
  – Nuclear Medicine
  – Ultrasound
  – Fluoroscopy
  – Electron Microscopy



MRI: brain

Ultrasound: a fetus in a womb

Medical Imaging

- CT – x-rays, the resulting images give anatomy structure.
- MRI – radio wave and magnetic field, the resulting images give anatomy structure.
- Nuclear Medicine – inject radioactive source into the body, then measure the radiation emitted from the body. The resulting images give physiological functions of the object.
- Ultrasound – high frequency sound waves (3-10 megahertz), real time.
- Fluoroscopy – a constant of x-rays, real time.
- EM – electron microscopy, small scales (molecular and cellular levels)

Biomedical Imaging Data

- The imaging data is a scalar/vector/tensor field over a 2D/3D rectilinear grid.

$$V = \{F(i, j, k) \mid i, j, k \text{ are indices of } x, y, z \text{ coordinates in a rectilinear grid}\}$$

Isocontour: $F(i, j, k) = \text{constant}$

Retrospective on 3D Medical Imaging

Medical imaging is a young field, which requires multi-disciplinary knowledge: physics, chemistry, medicine, mathematics, computer science, etc.

- In 1895, Wilhelm Roentgen discovered *x*-rays while experimenting with a Crookes tube, the precursor to the cathode ray tube common in video applications today. He immediately recognized the potential of *x*-ray radiation in diagnostic imaging and one of his earliest images is of the bones of his wife's hand.
- Roentgen's discovery was so noteworthy and revolutionary that he received a Nobel Prize in Physics within six years of announcing his initial work (1901).

Retrospective on 3D Medical Imaging

- The meaning and purpose of medical imaging has been to provide clinicians with the ability to see inside the body, to diagnose the human condition.
- The primary focus for much of this development has been to improve the quality of images for humans to evaluate.
- Only recently has computer technology become sufficiently sophisticated to assist in the process of diagnosis, which is a natural partnership between computer science and radiology.

Retrospective on 3D Medical Imaging

- Early in the 20th century, a Czech mathematician, Johann Radon derived a transform for reconstructing cross-sectional information from a series of planar projections taken from around the object.

- While this powerful theory had been known for over 50 years, the ability to compute the transform on real data was not possible until digital computers began to mature in the 1970s.

Retrospective on 3D Medical Imaging

- X-ray computed tomography was developed by Godfrey Hounsfield and Alan Cormack and 3D imaging emerged in 1972. They shared a Nobel Prize in Medicine in 1979.
- Their achievement is noteworthy because it is largely based on engineering, the theoretical mathematics and the underlying science had been described decades earlier.
- The contribution is in the application of mechanical engineering and computer science to complete what had previously only been conceived on paper.
- Clinical systems were patented in 1975 and began service immediately thereafter.

Retrospective on 3D Medical Imaging

- While *x*-ray techniques were being refined, organic chemists had been exploring the uses of nuclear magnetic resonance (NMR) to analyze chemical samples. NMR was studied by Felix Bloch and Edward Purcell in 1940s, and they shared the Nobel Prize in Physics in 1952.
- Paul Lauterbur, Peter Mansfield, and Raymond Damadian were the first to develop imaging applications from NMR phenomena. In 1972, Lauterbur created tomographic images of a physical phantom constructed of capillary tubes and water in a modified spectrometer. In 1975, Damadian was able to create animal images.
- The means of creating medical images using magnetic fields and radio waves was renamed Magnetic Resonance Imaging (MRI). Lauterbur and Mansfield won the 2003 Nobel Prize in Medicine. Damadian has not been honored, but his contribution is significant and should not be overlooked by us.

What is Physical Phantom?

- Phantoms are used to measure doses in radiation protections and evaluate radiotherapy treatment plans in the Monte Carlo model.

- Two kinds of phantoms in medical imaging
  - Physical phantoms (can be measured)
  - Computational phantoms

Retrospective on 3D Medical Imaging

- In the early 1970s, radiologists were simultaneously presented with the possibilities for slice (or tomographic) images in the axial plane from *x*-ray CT and from MRI.
- CT matured first because of the long development of *x*-ray technology.
- The difficulties and expense of generating strong magnetic fields remained an obstacle for clinical MRI scanners until engineers were able to produce practical superconducting magnets.
- While still expensive, MRI is now available worldwide, creating precise images of deep structures within the body, outlining the anatomy and physiology of internal objects other than bones.

Retrospective on 3D Medical Imaging

- MRI and CT have joined the established 3D imaging modalities of nuclear imaging and the growing field of volumetric ultrasound.

- The creation of new modalities with differing strengths has led to the need to align or register these multiple data streams.

Four Nobel Prizes on Medical Imaging

1. In 1901, Wilhelm Roentgen got the Nobel Prize in Physics due to his discovery of *x*-rays.
2. X-ray computed tomography was developed by Godfrey Hounsfield and Alan Cormack and 3D imaging emerged in 1972. They shared a Nobel Prize in Medicine in 1979.
3. Felix Bloch and Edward Purcell studied nuclear magnetic resonance (NMR) in 1940s, and they shared the Nobel Prize in Physics in 1952.
4. Paul Lauterbur and Peter Mansfield developed imaging applications from NMR phenomena. The means of creating medical images using magnetic fields and radio waves was renamed Magnetic Resonance Imaging (MRI). Lauterbur and Mansfield won the 2003 Nobel Prize in Medicine.

Medical Imaging Technology

- The majority of medical visualization involves the display of data acquired directly from a patient. The radiologist is trained to read relatively simple presentations of the raw data.
- The key to improving a diagnosis
  - careful crafting of the acquisition
  - applying the physics of radiology to maximize the contrast among the relevant tissues
  - suppressing noise, fog, and scatter that may obscure the objects of interest
- Improving the quality of the acquired data will fundamentally affect the quality of the resulting visualization.

Computed Tomography (CT)

- *X*-ray computed tomography (CT) is by far the most familiar form of 3D medical imaging.

- CT is formally referred to as:
  - Computer assisted tomography
  - Computerized axial tomography (CAT scanning)
  - Computerized transaxial tomography (CTAT)
  - Computerized reconstruction tomography (CRT)
  - Digital axial tomography (DAT)

Computed Tomography (CT)

- Since early in the 20th century, the mathematics for tomographic reconstruction from multiple views have been known.

- It took almost 50 years before the components required for *x*-ray computed tomography were sufficiently developed to make the procedure and the ensemble of instruments economically feasible.

Computed Tomography (CT)

- A CT scanner is a room sized *x-ray* instrument, requiring a shielded environment to protect the technologists and other clinic staff from exposure during routine use.

- The number of manufacturers of CT scanners has been steadily decreasing with only a handful of vendors providing them today, such as Siemens, GE.

- The cost ranges from $400k to well over $1M.

Computed Tomography (CT)

- Essential system components of a CT machine:
  - An accurately calibrated moving bed to translate the patient through the scanner.
  - An *x*-ray tube mounted in such a way to allow it to revolve about the patient.
  - An array of *x*-ray detectors (gas filled detectors or crystal scintillation detectors).

Computed Tomography (CT)

- The *x*-ray tube and detector array are mounted in a gantry that positions the detector assembly directly across from the *x*-ray source.
- The *x*-ray source is collimated by a pair of lead jaws so that the *x*-rays form a flat fan beam with a thickness determined by the operator.
- During the acquisition of one "slice" of data, the source-detector ring is rotated around the patient.

Computed Tomography (CT)

- The raw output from the detector array is back projected to reconstruct a cross-sectional transaxial image of the patient.

- By repositioning the patient, a series of slices can be aggregated into a 3D representation of the patient's anatomy.

Computed Tomography (CT)

- Within the last 15 years, there have been significantly advances in CT technology
  - Faster spiral acquisition and reduced dose to patients
  - Multislice detector arrays permitting simultaneous acquisition of several slices at a time
  - As small affordable detectors have become available, scanners have been designed with a fixed of x-ray detectors. The only remaining revolving part of the gantry is the x-ray tube.

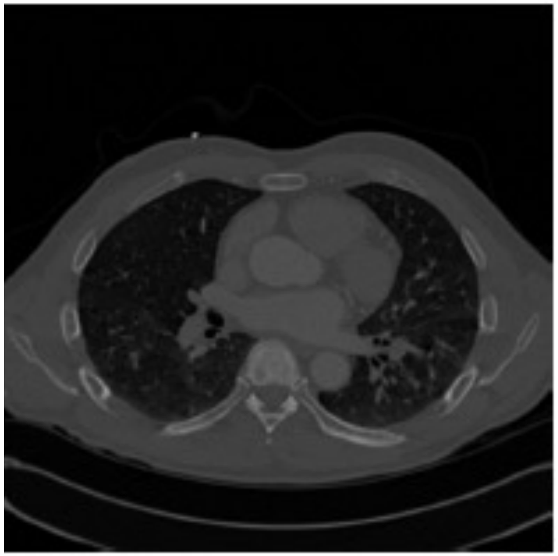
Computed Tomography (CT)

- Those significant advances in CT technology have enabled:
  - Faster image acquisition
  - Improving the patient throughput in a CT facility
  - Reducing artifacts from patient motion
  - Reducing absorbed dose by the patient
  - Combined with multiple layers of sensors in the detection ring, the new technologies are generating datasets of increasingly larger sizes.

Computed Tomography (CT)

- CT employs digital geometry processing to generate a 3D image of the internals of an object from a large series of 2D *x*-ray images, which are taken around a single axis of rotation.

- In CT, *x*-ray radiation is absorbed at different rates in different tissue types such as bone, muscle and fat. Dense objects absorb more photons.

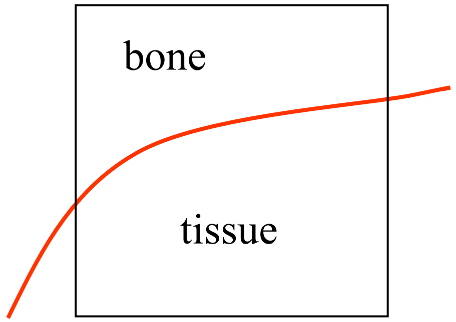


Computed Tomography (CT)

- A typical CT scanner can generally acquire data for a transaxial slice in a matter of seconds (1-5 seconds).
- Sampling resolution is either 256x256 or 512x512 voxels square. Sampling resolution in the longitudinal direction is bounded by physical limitations of collimating the photons into thin planes, e.g., 1mm.
- Spatial resolution is the size of a voxel or a pixel, e.g., 0.5-2mm. Attempting to achieve higher spatial resolution will lead to voxels with too little signal to accurately measure *x*-ray absorption, and introduce the problem of low signal-to-noise ratios.

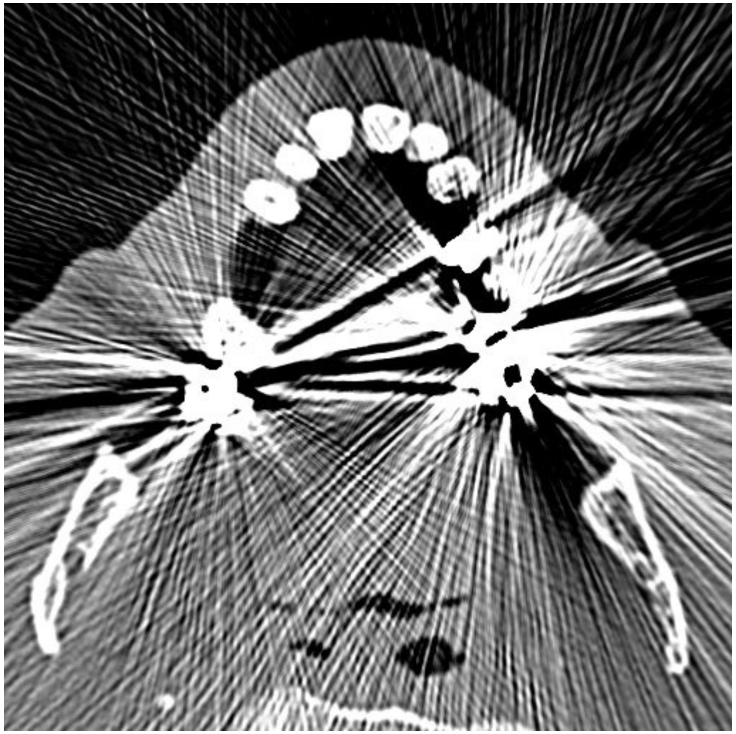
Aliasing Artifacts in CT

- Aliasing artifacts are introduced by the reconstruction and sampling procedure.
- Partial voluming, the condition where the contents of a pixel are distributed across multiple tissue types, blending the absorption characteristics of different materials.



Aliasing Artifacts in CT

- Patient motion generates a variety of blurring and ring artifacts during reconstruction.
- Artifacts introduced by *x*-ray modality, e.g., embedded dense objects such as dental fixtures and fillings or bullets lead to beam shadows and streak artifacts.



Metal streak artifacts due to the presence of amalgam dental fillings

Computed Tomography - Summary

- CT's primary benefit is the ability to separate anatomical structures at different depths within the body.

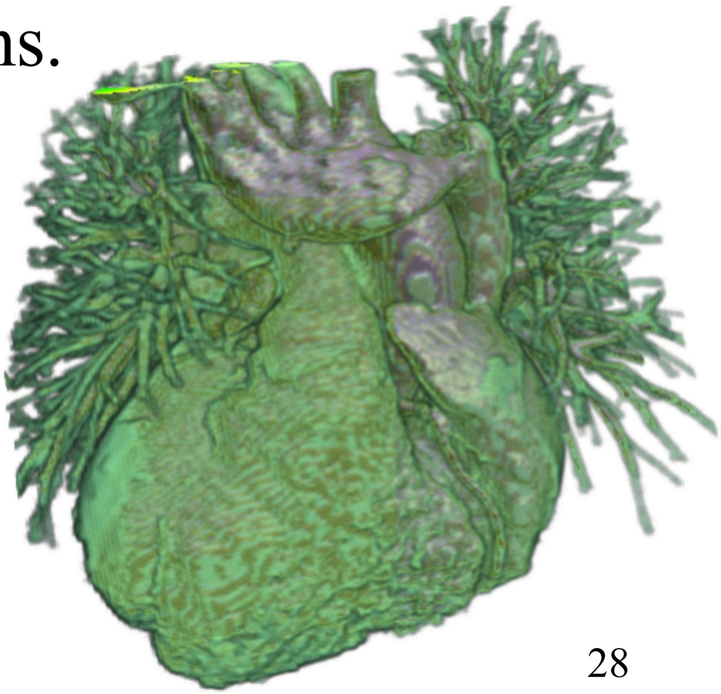
- CT uses *x*-rays to create images. The source/detector makes a complete 360 degree rotation about the subject obtaining a complete set of data from which images may be reconstructed.

Computed Tomography - Summary

- CT employs digital geometry processing to generate a 3D image of the internals of an object from a large series of 2D *x*-ray images.

- In CT, *x*-ray radiation is absorbed at different rates in different tissue types such as bone, muscle and fat. Dense objects absorb more photons.

- Multislice CT – multiple detector rings with increasing rotation speeds, e.g., 4, 8, 16, 32, 40 and 64 detector rings.



References

- Y. J. Zhang. Geometric Modeling and Mesh Generation from Scanned Images. Chapman & Hall/CRC Mathematical and Computational Imaging Sciences Series. CRC Press, Taylor & Francis Group. ISBN10: 1482227762, ISBN13: 978-1482227765. 2016
- http://en.wikipedia.org/wiki/Medical_imaging
- Yoo, Terry (Editor) (2004), Insight into Images, A K Peters, ISBN 1-56881-217-5. Chapter 1.
- Wilhelm Burger and Mark J. Burge (2007). Digital Image Processing: An Algorithmic Approach Using Java. Springer. ISBN 1846283795 and ISBN 3540309403