Medial Imaging Throughout the Years

Before the 20th century if we wanted to know what was inside someone we needed to cut them open.

Usually done without any anesthetic or much masks or gloves....
Medial Imaging Throughout the Years

Around 1900 Wilhelm Rontgen discovered the X-ray more or less by accident. He did not know what he had discovered, nobody did, but somehow these magical rays could see through many things including his hands.
Medial Imaging Throughout the Years

After that discovery everyone went nuts!!
Medial Imaging Throughout the Years

After a few decades, in which lots of people got sick from radiation exposure, we learned what x-rays were, we learned how to limit the x-ray dose and we learned how to take useful medical images safely.
Medial Imaging Throughout the Years

This first imaging method is called projection x-ray or projection radiography. It was a huge boom to medicine. For the first time we could look into a persons body without cutting them open.
Medial Imaging Throughout the Years

However, there was still a problem! Projection x-ray produced a projection or shadow of the x-rays as it travels through you. All depth information is lost! Useful but not as useful as it could be!
Enter Hounsfield and Cormack in the 1960’s with a really big idea!

Godfrey N. Hounsfield
Allan M. Cormack
Enter Hounsfield and Cormack in the 1960’s with a really big idea!

If instead of taking a single projection x-ray image what if we took lots of them at different angles looking through someone?
Medial Imaging Throughout the Years

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If I used the computer (pretty new idea concept in 1960s) would this be enough information to reconstruct a 2D slide of you?
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If I used the computer, pretty new idea concept in 1960s, would this be enough information to reconstruct a 2D slide of you?

Of course this worked! It is now called computed tomography (CT) and has saved countless lives. It also won Hounsfield and Cormack the 1979 Nobel Prize in Medicine.
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Of course this worked! It is now called computed tomography (CT) and has saved countless lives. It also won Hounsfield and Cormack the 1979 Nobel Prize in Medicine.

It is estimated that over 500,000 CT scanners are used worldwide producing over 200 million scans in 2011.
The success of CT began a revolution in computer based medical imaging systems (or tomographic systems).
Medical Imaging Throughout the Years

The success of CT began a revolution in computer based medical imaging systems (or tomographic systems).

- Magnetic Resonance Imaging (MRI)
- Optical coherence tomography (OCT)
- Positron Emission Tomography (PET)
Medical Imaging Throughout the Years

At its core modern medical imaging is more about medical instrumentation, signals and image processing than medicine!

It’s this guy ..

.. not this guy ..

... who should be credited for saving millions of lives each year.
Why do I love this course?

Two reasons:

(1) Medical imaging brings together a bunch of topics you have learned so far in a useful and elegant way. The subject combines physics, instrumentation, signals and systems, computer science, math, physiology, biology, and medicine for one noble purpose.

(2) There is just something magical about it!
ELEG 479/679  Introduction to Medical Imaging Systems

Course Description: This course introduces the physics, instrumentation, and signal processing methods used in X-ray (projection radiography), X-ray computed tomography, nuclear medicine (SPECT/PET), ultrasound imaging, and magnetic resonance imaging. Co-listed as BME479/ELEG479 and ELEG679 (3 credits)

Prerequisites: Signals and systems (ELEG305 or equivalent, preferred but not required). Open to graduate students and upper level UG students.

Instructor: Professor Mark Mirotznik, Evans 106, (302)831-4241, mirotzni@udel.edu

http://www.eecis.udel.edu/~mirotzni/

Course Schedule: Tuesday/Thursday 8:00-9:15 PM, Kirkbride 005

Office Hours: MWF. 10:00-11:00 or by appointment.

Course Website:


Homework policy: Homework will be assigned weekly and due the following week. Late submissions are not accepted. Exams will be primarily based on homework problems. Some assignments will include MATLAB programming of image reconstruction algorithms.

Grading Policy: Midterm Exam: 25 %, Final Exam: 25%, Homework Assignments: 25%, Project: 25%
Course Project: (GRAD STUDENTS ONLY)  This course will involve a research project. At the end of the semester, all students will be expected to make a 15-min presentation (with slides) on a particular topic in medical imaging. Students should select a topic, discuss with the instructor, and get approval within the first five weeks of class. A list of literature sources should be submitted to the instructor for approval by the ninth week of class. Students are expected to submit a written report on their project topic in addition to the presentation. The report should follow the guidelines for an IEEE conference paper, with sections for Introduction, Materials and Methods, Results, Discussion and Conclusion. Grades will be based on: knowledge of the subject and quality of background research, depth of critical analysis, clarity of explanation, and presentation style. For the project, students can select one of the following approaches:

1) Review a specific algorithm or technology for medical image formation, processing or analysis, demonstrate its uses, compare against alternative approaches, discuss the strengths and weaknesses, and suggest avenues for improvement.
2) Explore medical imaging applications for a specific organ or disease by identifying the clinical need, comparing the applicability of various imaging methods, and critically reviewing the latest research directions.
3) Review an emerging medical imaging modality, discuss the physics, instrumentation and image processing involved, describe potential applications, and discuss the strengths and weaknesses compared to existing imaging modalities.
Tentative Course Schedule

- Weeks 1-3: Overview of various medical imaging modalities (chap 1); Review of signals and systems basic concepts (chap 2); Image quality metrics (chap 3)
- Week 4: Physics of radiography (chap 4)
- Week 5: Projection radiography (conventional X-ray) (chap 5)
- Weeks 6-7: X-ray computed tomography (CT): Instrumentation; Image reconstruction (Radon transform, back projection, filtered back-projection); Image quality (chap 6)
- Week 7: Midterm Review and Exam
- Week 8: Physics of magnetic resonance (chap 12)
- Weeks 9-12: Magnetic resonance imaging (MRI) systems (chap 13): instrumentation, data acquisition, image reconstruction, image quality. Functional MRI
- Week 13: Physics of ultrasound (chap 10)
- Week 14: Ultrasound imaging (chap 11)
- Week 15: Final Review and Final Exam
Course breakdown

- Biomedical Imaging is a multi-disciplinary field involving
  - Physics (matter, energy, radiation, etc.)
  - Math (linear algebra, calculus, statistics)
  - Biology/Physiology
  - Engineering (implementation)
  - Signal processing and Image processing (image reconstruction and enhancement and analysis)

- Course breakdown:
  - 1/3 physics
  - 1/3 instrumentation
  - 1/3 signal processing

- Understand the imaging system from a “signals and systems” point of view
Student Honesty Policy

• I take cheating and plagiarism very seriously!!
• If you are caught:
  
  ➢ submitting other peoples work as if it was your own
  ➢ copying homework/project/exam work from others
  ➢ or any other form of cheating defined within the student honestly policy of the university

• You will
  
  • get a failing grade in the course
  • be put up on charges of academic dishonesty at the University level
What is Imaging?
What is an Imaging System?

I think an imaging system is simply a device that tries to represent a spatial representation of some property (or properties) of an object or objects.
What is an Imaging System?

I think an imaging system is simply a device that tries to represent a spatial representation of some property (or properties) of an object.

Let's look at some examples and try to use this definition to describe the imaging system.
What is an Imaging System?

I think an imaging system is simply a device that tries to represent a spatial representation of some property (or properties) of an object.

Question: What properties of an object or scene does our human visual system try to spatially represent?
What is an Imaging System?

I think of an imaging system as simply a device that tries to represent a spatial representation of some property (or properties) of an object.

Q: What properties of an object does our human visual system try to spatially represent?
A: The spatial and spectral reflectance, transmission and absorption of light within the visible portion of the EM spectrum (430–790 THz)
What is an Imaging System?

I think of an imaging system as simply a device that tries to represent a spatial representation of some property (or properties) of an object.

Q: What spatial representation (or spatial mapping) of that property does our human visual system use?
What is an Imaging System?

I think of an imaging system as simply a device that tries to represent a spatial representation of some property (or properties) of an object.

Q: What spatial representation of that property does our human visual system use?
A: 2D spatial distribution of electrical impulses on the rods and cones of our eye. Those signals are transmitted to the brain and processed to create what we see.
What is an Imaging System?

A: 2D spatial distribution of electrical impulses on the rods and cones of our eye. **Those signals are transmitted to the brain and processed to create what we see.**

Who is this?
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Who is this?
What is an Imaging System?

I think of an imaging system as simply a device that tries to represent a spatial representation of some property (or properties) of an object.

Infrared Camera

What properties of an object does an infrared camera measure?
What is an Imaging System?

I think of an imaging system as simply a device that tries to represent a spatial representation of some property (or properties) of an object.

Q. What properties of an object does an infrared camera measure?

A. It measures the spatial distribution of infrared energy emitted from an object due to its temperature. The typical spectral bands have wavelengths 1 to 2 micros, 3 to 5 microns and 8 to 12 microns.
I think of an imaging system as simply a device that tries to represent a **spatial representation of some property (or properties)** of an object.

**Q:** What spatial representation of that property does a thermal camera use?
What is an Imaging System?

I think of an imaging system as simply a device that tries to represent a spatial representation of some property (or properties) of an object.

Q: What spatial representation of that property does a thermal camera use?

A: The integrated thermal energy from a 3D object is converted to electrical signals on a 2D detector array and then processed into an image by the backend electronics.
What is an Imaging System?

I think of an imaging system as simply a device that tries to represent a spatial representation of some property (or properties) of an object.

RADAR Image

What properties of an object does a RADAR measure?
What is an Imaging System?

I think of an imaging system as simply a device that tries to represent a spatial representation of some property (or properties) of an object.

Q. What properties of an object does a RADAR measure?

A. It measures the reflectance of an electromagnetic pulse within the radiofrequency and microwave bands.
Radar Frequencies
What is an Imaging System?

I think of an imaging system as simply a device that tries to represent a spatial representation of some property (or properties) of an object.

Q: What spatial representation of that property does a RADAR use?

A: The RADAR scans a narrow (pencil like) beam in a direction \((\theta, \phi)\) and records the reflectance at that angle inside a computer. It creates an image by putting all the recorded data together for every angle scanned. RADAR also can use the time it takes for the RADAR pulse to return as a method of determining distance to an object. So RADAR can actually create 3D spatial representations of a scene.
What is an Imaging System?

I think of an imaging system as simply a device that tries to represent a spatial representation of some property (or properties) of an object.

SONAR Image

What properties of an object does a SONAR measure?
What is an Imaging System?

I think of an imaging system as simply a device that tries to represent a spatial representation of some property (or properties) of an object.

Q. What properties of an object does a SONAR measure?

A. It measures the reflectance of a pulse of high frequency sound waves.
What is an Imaging System?

I think of an imaging system as simply a device that tries to represent a spatial representation of some property (or properties) of an object.

Q: What spatial representation of that property does a SONAR use?

A: SONAR scans a narrow (pencil like) beam in a direction $(\theta, \phi)$ and records the reflectance just like RADAR. It creates an image by putting all the recorded data together for every angle scanned. SONAR also can use the time it takes for the sound pulse to return as a method of determining distance to an object. So SONAR can also create 3D spatial representations of a scene.
## What is an Imaging System?

<table>
<thead>
<tr>
<th></th>
<th>What property does it image?</th>
<th>How does it represent an image?</th>
<th>Is this passive or active imaging?</th>
<th>Advantages?</th>
<th>Disadvantages?</th>
</tr>
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<tbody>
<tr>
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<td>2D representation of electrical impulses in the retina</td>
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<td></td>
</tr>
<tr>
<td><strong>IR Camera</strong></td>
<td>Emission of light in the infrared portion of the EM spectrum do the temperature</td>
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<td></td>
<td></td>
<td></td>
</tr>
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<td><strong>RADAR</strong></td>
<td>Reflectance of an EM pulse in the RF&amp; microwave portion of the EM spectra</td>
<td>2D or 3D table of numbers found by scanning the radar beam</td>
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<td>Human eye</td>
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<td>passive</td>
<td>• good resolution</td>
<td>• needs external illumination</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• good contrast</td>
<td>• can’t see through much</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• lots of illumination (sun)</td>
<td></td>
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<td>2D array of pixels in a IR detector array (focal plane array)</td>
<td>passive</td>
<td>• decent resolution</td>
<td>• relatively poor contrast (depends on difference in temperature)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• temperature based so you can see at night</td>
<td>• can’t see through much</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• can be used to distinguish between different chemicals (spectroscopy)</td>
<td>• hard to see far away</td>
</tr>
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<td>RADAR</td>
<td>Reflectance of an EM pulse in the RF &amp; microwave portion of the EM spectra</td>
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<td>active</td>
<td>• see through lots of stuff (rain, fog, clouds, dust, walls)</td>
<td>• relatively poor resolution</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• good contrast between metal and non-metal.</td>
<td>• lots of non-metallic things looks the same</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<td>• does not work out of water (or stuff that is like water).</td>
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What is an Imaging System?

So what is common among imaging systems?

Some property of an object or scene exists in 4D $O(x,y,z,t)$ that we wish to know about.
What is an Imaging System?

So what is common among imaging systems?

Some physics and technology let us interrogate that property

Some property of an object or scene exists in 4D O(x,y,z,t) that we wish to know about
What is an Imaging System?

So what is common among imaging systems?

1. Some property of an object or scene exists in time and space that we wish to know about.

2. Some external energy, physics and technology are used to let us interrogate that property to some degree (never perfectly).

3. Some instrument is used to let us measure the response from the external interrogation of the object.
What is an Imaging System?

So what is common among imaging systems?

1. Some property of an object or scene exists in time and space that we wish to know about.

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4. Some instrument is used to process the measured data to finally arrive at our output image.
What is an Imaging System?

So how do we as engineers look at this concept?

1. Some property of an object or scene exists in time and space that we wish to know about: \( O(x,y,z,t) \)

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Some external energy, physics and technology are used to let us interrogate that property to some degree (never perfectly)

$$A_1(x,y,z,t) \rightarrow F_2(A_1(x,y,z,t)) \rightarrow A_2(x,y,z,t) \text{ or } A_2(u,v) \text{ or } A_2(u,v,f)$$

Some instrument is used to let us measure the response from the external interrogation of the object

This not look anything like the original object

Some external energy, physics and technology are used to let us interrogate that property to some degree (never perfectly)
What is an Imaging System?

So how do we as engineers look at this concept?

Some instrument is used to let us measure the response from the external interrogation of the object

$A_2(x,y,z,t)$ or $A_2(x,y,z)$ or $A_2(u,v)$ or $A_2(u,v,f)$

$F_3(A_2) \rightarrow I(x,y,z,t)$ or $I(x,y,z)$ or $I(x,y)$

Some instrument is used to process the measured data to finally arrive at our output image
What is an Imaging System?

So how do we as engineers look at this concept?

**A signals/systems approach towards imaging allows us (as Engineers) to**

- Gain a better understanding of how the images form and what their limitations are
- Determine how to better design imaging systems to optimize some particular performance metric (e.g. resolution, contrast between healthy tissue and disease ..)

\[
F(O(x,y,z,t)) = F_3(F_2(F_1(O(x,y,z,t))))
\]
Overall Concept

object → imaging device → data → imaging algorithm → reconstructed cross-sectional image
What is Medical Imaging?

- Using an instrument to see the inside of a human body
  - Non-invasive
  - Some with exposure to small amount of radiation (X-ray, CT and nuclear medicine)
  - Some w/o (MRI and ultrasound)
- The properties imaged vary depending on the imaging modality
  - X-ray (projection or CT): attenuation coefficient to X-ray
  - Nuclear medicine (PET, SPECT): distribution of introduced radio source
  - Ultrasound: sound reflectivity
  - MRI: hydrogen proton density, spin relaxation
Projection vs. Tomography

- Projection:
  - A single image is created for a 3D body, which is a “shadow” of the body in a particular direction (integration through the body)
Projection vs. Tomography

- **Tomography**
  - A series of images are generated, one from each slice of a 3D object in a particular direction (axial, coronal, sagittal)
  - To form an image of each slice, projections along different directions are first obtained, images are then reconstructed from projections (back-projection, Radon transform)
Anatomical vs. Functional Imaging

- Some modalities are very good at depicting anatomical (bone) structure
  - X-ray, X-ray CT
  - MRI
- Some modalities do not depict anatomical structures well, but reflect the functional status (blood flow, oxygenation, etc.)
  - Ultrasound
  - PET, functional MRI

(a) CT  (b) MRI  (c) PET
An MRI scan shows you that you have a brain

A PET scan shows that you use it
Imaging Modalities Overview

CT

MRI / fMRI

Nuclear

PET

SPECT

Ultrasound

X-ray

magnetic spin

metabolic tracer X-ray emission

sound waves
Wilhelm Conrad Röntgen

- 8 November 1895: discovers X-rays.
- 22 November 1895: X-rays Mrs. Röntgen’s hand.
- 1901: receives first Nobel Prize in physics

An early X-ray imaging system:

Note: so far all we can see is a projection across the patient:
Projection Radiography

Figure 1.1

*Medical Imaging Signals and Systems*, by Jerry L. Prince and Jonathan Links.
# Projection Radiography

- **Year discovered:** 1895 (Röntgen, NP 1905)
- **Form of radiation:** X-rays = electromagnetic (photons)
- **Energy / wavelength of radiation:** 0.1 – 100 keV / 10 – 0.01 nm (ionizing)
- **Imaging principle:** X-rays penetrate tissue and create "shadowgram" of differences in density.
- **Imaging volume:** Whole body
- **Resolution:** Very high (sub-mm)
- **Applications:** Mammography, lung diseases, orthopedics, dentistry, cardiovascular, GI
History: Computed Tomography

The breakthrough:

- acquiring many projections around the object enables the reconstruction of the 3D object (or a cross-sectional 2D slice)

CT reconstruction pioneers:

- 1917: Johann Radon establishes the mathematical framework for tomography, now called the Radon transform.
- 1963: Allan Cormack publishes mathematical analysis of tomographic image reconstruction, unaware of Radon’s work.
- 1972: Godfrey Hounsfield develops first CT system, unaware of either Radon or Cormack’s work, develops his own reconstruction method.
- 1979 Hounsfield and Cormack receive the Nobel Prize in Physiology or Medicine.
Computed Tomography: Concept

more:
Computed Tomography: Past and Present

Image from the Siemens Siretom CT scanner, ca. 1975
- 128x128 matrix.

Modern CT image acquired with a Siemens scanner
- 512x512 matrix
3D Visualization

Reconstructed object enables:
- Enhanced X-ray visualization from novel views:
  - Maximum Intensity (MIP) visualization:
  - Shaded object display:
Virtual colonoscopy, endoscopy, arthroscopy
Virtual therapy and surgery planning
Training platform
Computed Tomography

- Year discovered: 1972 (Hounsfield, NP 1979)
- Form of radiation: X-rays
- Energy / wavelength of radiation: 10 – 100 keV / 0.1 – 0.01 nm (ionizing)
- Imaging principle: X-ray images are taken under many angles from which tomographic ("sliced") computed views are
- Imaging volume: Whole body
- Resolution: High (mm)
- Applications: Soft tissue imaging (brain, cardiovascular, GI)
Nuclear Medicine

- Images can only be made when appropriate radioactive substances (called radiotracer) are introduced into the body that emit gamma rays.
- A nuclear medicine image reflects the local concentration of a radiotracer within the body.
- Three types
  - Conventional radionuclide imaging or scintigraphy
  - Single photon emission computed tomography (SPECT)
  - Positron emission tomography (PET)
Nuclear Medicine

- What do you see?
Nuclear Medicine

- Year discovered: 1953 (PET), 1963 (SPECT)
- Form of radiation: Gamma rays
- Energy / wavelength of radiation: > 100 keV / < 0.01 nm (ionizing)
- Imaging principle: Accumulation or "washout" of radioactive isotopes in the body are imaged with x-ray cameras.
- Imaging volume: Whole body
- Resolution: Medium – Low (mm - cm)
- Applications: Functional imaging (cancer detection, metabolic myocardial infarction)
Ultrasound Imaging

- High frequency sound are emitted into the imaged body, time and strength of returned sound pulses are measured.
- Comparatively inexpensive and completely non-invasive.
- Image quality is relatively poor.
History: Ultrasound

1942: Dr. Karl Theodore Dussik,
- transmission ultrasound investigation of the brain

1955: Holmes and Howry
- Subject submerged in water tank to achieve good acoustic coupling

image of normal neck

1959: Automatic scanner, Glasgow

twin gestation sacs (s) and bladder (B).
Ultrasound: Present

3D Ultrasound

Intravascular ultrasound

Doppler ultrasound
Ultrasound Imaging

- Year discovered: 1952 (clinical: 1962)
- Form of radiation: Sound waves (non-ionizing) Not EM radiation!
- Frequency / wavelength of radiation: 1 – 10 MHz / 1 – 0.1 mm
- Imaging principle: Echoes from discontinuities in tissue density/speed of sound registered.
- Imaging volume: < 20 cm
- Resolution: High (mm)
- Applications: Soft tissue, blood flow (Doppler)
1946: Felix Bloch (Stanford) and Edward Purcell (Harvard) demonstrate nuclear magnetic resonance (NMR)

1973: Paul Lauterbur (Stony Brook University) published first MRI (Magnetic Resonance Imaging) image in Nature.
  - receives the Nobel Prize in Physiology or Medicine in 2003

Late 1970's: First human MRI images conceived

Early 1980's: First commercial MRI systems available

1993: Functional MRI in humans demonstrated
MRI Concept

MRI measures the effects of magnetic properties of tissue
  - these effects are tissue-specific
  - also specific to blood perfusion / oxygenization (functional MRI)

MRI is very versatile (but also more expensive than CT)
MRI Applications

Cardiac MRI
- measures the distortion of “tags” to assess motion of the heart tissue

Diffusion Tensor Imaging
- measures the diffusion of water
- allows the tracking of nerve fibers in the brain (white matter)
Functional MRI

- allows to assess brain activity during certain tasks
- valuable for brain functional studies, but also for surgery planning and diagnosis
MRI Applications

MR Spectroscopy
- measures the distribution of chemicals in each "voxel" of the brain
MRI Applications

MR Angiography

- magnetizes the bolus of blood, enhances vessels
- similar effects to X-ray angiography, but non-invasive
Magnetic Resonance Imaging

- Year discovered: 1945 ([NMR] Bloch, NP 1952)
  1973 (Lauterbur, NP 2003)
  1977 (Mansfield, NP 2003)
  1971 (Damadian, SUNY DMS)

- Form of radiation: Radio frequency (RF)
  (non-ionizing)

- Energy / wavelength of radiation: 10 – 100 MHz / 30 – 3 m
  (~10-7 eV)

- Imaging principle: Proton spin flips are induced,
  and the RF emitted by their response (echo) is detected.

- Imaging volume: Whole body

- Resolution: High (mm)

- Applications: Soft tissue, functional imaging
Waves Used by Different Modalities

**Magnetic Resonance Ultra Sound**

- Wavelength (in meters): $10^3$ to $10^1$
- Size of wavelength: Longer
- Common name of wave: Radio Waves
- Sources: FM Radio, Microwave Oven
- Frequency (waves per second): $10^9$ to $10^8$
- Energy of one photon (electron volts): $10^{-6}$ to $10^{-7}$

**Optical Tomography**

- Size of wavelength: $10^{-1}$ to $10^{-3}$
- Common name of wave: Infrared, Ultraviolet
- Sources: Light Bulb
- Frequency (waves per second): $10^{13}$ to $10^{14}$
- Energy of one photon (electron volts): $10^{3}$ to $10^{4}$

**X-Ray Mammography**

- Size of wavelength: $10^{-9}$ to $10^{-10}$
- Common name of wave: Soft X-rays, Gamma Rays
- Sources: X-Ray Machines
- Frequency (waves per second): $10^{19}$ to $10^{20}$
- Energy of one photon (electron volts): $10^{6}$