University of Waterloo
Department of Electrical & Computer Engineering

ECE 700 T11 – Principles of Biomedical Imaging

Course Summary

This graduate-level course provides an in-depth exploration of the physical principles underlying modern medical imaging techniques. Students will learn about the interaction of various types of radiation with matter, as well as the workings of various imaging modalities including radiology, computerized tomography (CT), magnetic resonance imaging (MRI), nuclear imaging, and ultrasound imaging. The course also covers essential topics on medical imaging data formats, specifically DICOM, and the Picture Archiving and Communication Systems (PACS). Designed for graduate students in electrical and computer engineering, biomedical engineering, physics, and related fields, the course aims to equip participants with the knowledge and skills to critically evaluate and apply imaging technologies in clinical or research settings.

Course Objectives

- To understand the fundamental physical principles that underpin different medical imaging technologies.
- To learn the advantages, limitations, and clinical applications of each imaging modality.
- To develop skills in analyzing, handling, and interpreting medical imaging data.
- To apply theoretical knowledge to practical and programming assignments, enhancing problem-solving skills within the context of medical imaging.

Learning Outcomes

This course is ideal for graduate students in electrical and computer engineering, biomedical engineering, systems design, medical physics, and related fields who are interested in the technical foundations of medical imaging technologies and their application in healthcare. Participants will leave the course with a solid understanding of medical imaging physics, capable of critically evaluating and applying imaging technologies in a clinical or research setting. They will gain hands-on experience with medical imaging data and develop both analytical and problem-solving skills applicable to their future careers.

Course Structure

The course is structured over 36 academic hours, supplementing lectures with home assignments that include both theoretical questions and practical programming tasks. The course will culminate in a final project, offering students an opportunity to apply comprehensive knowledge gained throughout the course to a real-world problem or research topic in medical imaging.

Detailed Syllabus

Subject	Topics	Duration
Introduction to Medical Imaging	History of medical imaging, medical imaging modalities, anatomical vs functional imaging, spatial resolution, dynamic range, signal-to-noise and contrast-to-noise ratios, imaging artifacts.	1 hour
Interaction of Radiation with Matter	Types of radiation, ionizing vs non-ionizing radiation, attenuation, absorption and interactions of X- and γ rays with biological tissue, linear and mass attenuation coefficients, equivalent and effective dozes.	2 hours
Diagnostic Radiology	Generation and detection of X-rays, energy spectrum of X-rays, contrast mechanisms and image formation in planar radiography, fluoroscopic imaging, contrast and doze in X-ray radiography, clinical applications.	3 hours
Computed Tomography (CT)	Principles of tomographic imaging, Beer's law, spiral/helical CT, multi-slice CT, image reconstruction techniques in CT, filtered back-projection, fan/cone beam reconstruction methods, image quality and artifacts, doze optimization, clinical applications.	6 hours
Magnetic Resonance Imaging (MRI)	Nuclear magnetic resonance, Bloch equations, image acquisition, k-space formalism and image reconstruction, pulse sequence protocols, tissue relaxation times and contrast mechanisms, multi-slice/parallel imaging, fast MRI protocols, functional MRI, diffusion-weighted MRI, imaging artifacts, clinical applications.	6 hours
Nuclear Imaging	Radiotracers and their properties, gamma camera, planar scintigraphy, single photon emission computed tomography (SPECT), data processing and image reconstruction in SPECT, positron emission tomography (PET), data processing and image reconstruction in PET, clinical applications of SPECT and PET.	6 hours
Ultrasound Imaging	Physical principles of ultrasound, acoustic impedance, specular reflection and diffusive scattering, the Born approximation, acoustic attenuation and dispersion, single element transducers and transducer arrays, diagnostic scanning modes, Doppler ultrasound, harmonic imaging, safety and clinical applications.	6 hours
Optical Microscopy and Digital Histology	Principles of optical microscopy, bright/dark field microscopes, phase difference microscopes, polarized light microscopes, interference microscopes, fluorescent microscopes, imaging resolution, contrast mechanisms, applications in digital pathology.	3 hours
Data Formats and PACS	Overview of DICOM standards, image storage, handling, and communication through picture archiving and communication system (PACS).	3 hours

Recommended Literature

- N. Smith and A. G. Webb, *Introduction to Medical Imaging: Physics, Engineering, and Clinical Applications*, Cambridge University Press, 2011.
- C. L. Epstein, *Introduction to the Mathematics of Medical Imaging*, SIAM, 2008.
- E. Seeram, *Computed Tomography: Physical Principles, Clinical Applications, and Quality Control*, Saunders/Elsevier, 2009.
- V. Kuperman, *Magnetic Resonance Imaging: Physical Principles and Applications*, Elsevier Science, 2000.
- S. R. Cherry, J. A. Sorenson, M. E. Phelps, *Physics in Nuclear Medicine*, Elsevier/Saunders, 2012.
- H. Azhari, *Basics of Biomedical Ultrasound for Engineers*, Wiley, 2010.
- Y. Sucaet, W. Waelput, *Digital Pathology*, Springer International Publishing, 2014.
- O. Pianykh, *Digital Imaging and Communications in Medicine (DICOM): A Practical Introduction and Survival Guide*, Springer Berlin Heidelberg, 2009.

Marking Scheme

The total course mark is divided equally between 4 home assignments (10% each), one end-of-the-term quiz (10%), and a final project (50%). This marking scheme ensures a balanced assessment of students' performance throughout the course, with equal weights given to its academic and applied components. The home assignments are distributed throughout the course, with specific due dates aligned with the relevant lecture topics. The quiz is held on the last week of classes. The final project is introduced in Week 5, with preliminary ideas and planning, followed by progress check-ins in Week 7, and final submission scheduled for the last week of final exams.

Final Project

The final project aims to assess a thorough understanding of the course material as well as to push students to explore real-world applications, recent advancements, and innovative research areas within medical imaging.

The final projects are completed in groups of two students formed according to their project and partner preferences. Each group is assigned a project from a list of available research topics based on their preferences. Each group is expected to submit a final report (50% of total mark) which is evaluated based on the following criteria.

1. Project Proposal (clarity of objectives, feasibility and scope, originality) – 10%
2. Literature Review/Research Background (comprehensiveness of review, relevance to the project, critical analysis) – 10%
3. Methodology/Implementation (appropriateness of methods, detailed description of process, execution of methodology) – 10%
4. Results/Findings— (clarity and organization of results, interpretation and analysis, validity and reliability of findings) – 10%
5. Presentation (structure and organization, clarity and depth of content) – 10 %

Each group is required to choose one from the list of five project subjects which are:

Project	Description	Objective
Comparative Study on Imaging Modalities	Students select two or more imaging modalities (e.g., MRI vs. CT) and conduct a comparative study analyzing various aspects such as image quality, diagnostic value, cost-effectiveness, patient safety, and typical clinical applications.	To understand the strengths and limitations of different imaging technologies in various clinical scenarios.
Innovation in Medical Imaging Technology	Students explore recent advancements or emerging technologies in medical imaging (such as AI applications in imaging, development of new contrast agents, or breakthroughs in reducing radiation exposure) and evaluate their potential impacts on diagnostics and treatment.	To engage with current research and development in the field and assess the future of medical imaging technologies.
Development of a Low-cost Imaging Solution	Encourage students to design a conceptual model for a low-cost imaging system or technique, focusing on applications in underserved areas or for specific conditions that are currently challenging to diagnose. This can involve literature research on existing technologies, design principles, and potential innovations to reduce costs while maintaining effectiveness.	To foster innovation and problem-solving skills with a focus on accessibility and global health challenges.
Image Processing and Analysis Project	Using software tools (e.g., MATLAB, Python with libraries like OpenCV, or ImageJ), students apply image processing techniques to medical images to solve a specific problem, such as improving image quality, automating disease detection, or quantifying changes over time.	To develop practical skills in handling and analyzing medical imaging data and to understand the role of image processing in enhancing diagnostic accuracy.
Case Study Evaluation	Students are presented with a series of case studies involving medical images from various modalities. They must diagnose conditions based on the images, justify their diagnostic approach, and suggest follow-up diagnostic plans.	To apply theoretical knowledge to practical, real-world situations, while enhancing diagnostic reasoning and clinical decision-making skills.