Chapter 1

Introduction

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The design and manufacturing of modern medical devices requires knowledge of several disciplines, ranging from physics, over material science, to computer science. Thus, designing a single lecture as an introduction to medical engineering faces a lot of challenges. Nonetheless, the manuscript *Medical Imaging Systems – An Introductory Guide* aims at being a complete and comprehensive introduction to this field for students in the early semesters. Medical imaging devices are by now an integral part of modern medicine, and have probably already been encountered by all students in their personal life.

This book does not simply summarize the content of the lecture held in Erlangen. Instead, it should be understood as additional material to gain a better understanding of the theory that is covered in the lecture. To give a complete introduction, the lecture notes also cover basic math and physics that are required to understand the underlying principles of the imaging devices. However, we try to limit this to the very basics. Obviously, this is not sufficient to describe everything in the appropriate level of detail. For this reason, we introduced *geek boxes* (cf. Geek Box 1.1) that contain optional additional background information. This concept will be used in all chapters of the book which are summarised in the following sections.

Chap. 2 and 3 of this book cover an introduction to signal and image processing. Chap. 2 introduces the concepts of filtering, convolution, and Fourier transforms for 1-D signals, all of which are fundamental tools that are later on used across the entire book. We try to explain why these concepts are required and as most image processing is digital also emphasize the discrete algorithmic counter parts. At the beginning of Chap. 3, the transition to images is made, and therefore also the transition from 1-D to 2-D. The chapter

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Geek Box 1.1: Geek Boxes

We designed the manuscript to be readable from the first semester on. However, we felt that we need to demonstrate that there is much more depth that we could go into. In order not to confuse a less experienced reader, we omitted most equations and math from the main text and relocated them to *geek boxes* that go into more detail and give references to further reading. In addition, we also refresh concepts that are already known to most readers. Nonetheless, the important concepts are already mentioned in the main text. This way, the reader can return to this book at a time when these concepts are introduced, e. g., in more advanced math courses seemingly unrelated to medical imaging. As such this book can be read twice: once omitting all geek boxes to get an overview on the field and a second time with a more throrough focus on the mathematical details.

covers the basics of image processing and explains how different image transformations such as edge detection and blurring are implemented as image filters using convolution.

The following chapters cover examples for imaging devices using standard optics. In this book, endoscopy and microscopy are discussed as typical modalities of this genre. Endoscopes, see Chap. 4, were among the first medical imaging devices that were used. Images can be acquired by using long and flexible optical fibers that are able to transport visible light through the body of a patient.

Microscopes also use visible light. However, tissue samples or cells have to be extracted from the body first, e. g., in a biopsy. Then the microscope's optics are used to acquire images at high magnifications that allow the imaging of individual cells and even smaller structures. Microscopes and the principles of optics are described in Chap. 5.

Magnetic resonance imaging (MRI), see Chap. 6 uses electromagnetic waves to excite water atoms inside the human body. Once the excitation is stopped, the atoms return to their normal state and by doing so emit the same electromagnetic radio wave that was used to excite them. This effect is called nuclear magnetic resonance. Using this effect, an MRI image is obtained. Fig. 1.1 shows a state-of-the-art MR scanner.

X-ray imaging devices, see Chap. 7, use light of very high energy. However, the light is no longer visible for the human eye. The higher energy of the light allows for a deeper penetration of the body. Due to different absorption rates of X-rays, different body tissues can be distinguished on X-ray images. Tissues with high X-ray absorption, e. g., bones, become visible as bright structures in X-ray projection images. Today, X-rays are among the most widely spread

Figure 1.1: MRI is based on nuclear magnetic resonance which does not involve ionizing radiation. For this reason MRI is often used in pediatric applications. Image courtesy of Siemens Healthineers AG.

Figure 1.2: X-ray projection images are one of the most wide-spread imaging modalities. Image courtesy of Siemens Healthineers AG.

Figure 1.3: Modern CT systems allow even scanning of the beating heart. Image courtesy of Siemens Healthineers AG.

medical imaging technologies. An example for an X-ray imaging device is shown in Fig. 1.2.

Computed tomography (CT) uses X-rays to reconstruct slice and volume data as described in Chap. 8. The total absorption along the path of an X-ray through the body is actually given by the sum of absorptions by tissues with different absorption characteristics along its path. Thus, a measurement of the absorptions of X-rays from different directions allows for a reconstruction of slice images through the patient's body. In doing so, much better contrast between types of soft tissue is obtained. One is even able to differentiate between different tissue types such as brain and brain tumor. Once several slices are combined, the entire volume can be reconstructed by stacking the slices, which is then referred to as a 3-D image. Fig. 1.3 shows a state-of-the-art CT system with a gantry that rotates at 4 Hz.

X-rays essentially are electromagnetic waves that can be described by their amplitude, wavelength, and phase. Phase contrast imaging exploits the effect that an X-ray passing through tissue is not only influenced by absorption, but that also the phase of the electromagnetic wave is shifted. Chap. 9 shows that the phase shift of X-rays can be used to visualize the tissue the X-rays have passed. Today, phase contrast imaging is not yet used in clinical practice. In fact, due to the high requirements on the type of irradiation, such images often require a synchrotron as the source of the radiation. However, new developments in research now allow to generate phase contrast images using a normal clinical X-ray tube, which renders the application clinically feasible. At present, technical limitations allow only the scanning of small specimen such as peanuts and the mechanical design is still challenging. First image results indicate that the modality might be of high clinical relevance. Fig. 1.4 shows the reconstruction of peanut fibers that are in the range of

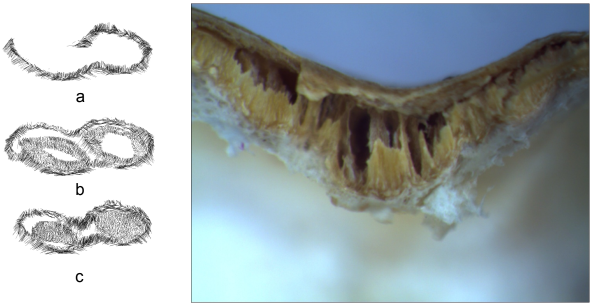

Figure 1.4: An X-ray dark-field setup can be used to reconstruct the orientation of fibers that are smaller than the detector resolution. The image on the left shows the reconstructed fiber orientation in different layers of a peanut. The image on the right shows a microscopic visualization of the waist of the peanut (picture courtesy of ECAP Erlangen).

Figure 1.5: Modern SPECT/CT systems combine different modalities to achieve multi-modal imaging. Image courtesy of Siemens Healthineers AG.

several micrometers. Phase contrast allows for a reconstruction of these fibers, although the resolution of the used imaging device based on the absorption of X-rays was only 0.1 mm.

Emission tomography, described in Chap. 10, is used for imaging different bodily functions. It uses *tracers*, which are molecules that are marked with radioactive atoms. For example one can introduce a radioactive atom into a sugar molecule. When this tracer is consumed by the body it will follow the normal metabolism, and its path through the body can be followed. While sugar consumption is normal in certain parts of the body such as the muscles or the brain, tumors also require a lot of sugar for their growth. Thus, emis-

Figure 1.6: A typical ultrasound system as it can be found in clinics worldwide. Image courtesy of Siemens Healthineers AG.

sion tomography enables us to see anomalies in sugar consumption within the body which is useful to spot tumors or metastases. Fig. 1.5 shows a combined single-photon emission computed tomography (SPECT) / CT system that combines emission tomography with X-ray CT.

Ultrasound (US) uses high-frequency sound waves to penetrate bodily tissue. The sound waves are emitted from a probe that is in direct contact with the body. The same probe is then also used to measure the reflections of the sound waves. Given the time between the emission of the sound wave and the measurement of the reflection, one is able to reconstruct how deep the wave penetrated the tissue. US is one of the most wide-spread imaging modalities as it is rather inexpensive compared to other imaging modalities. Fig. 1.6 shows a clinical ultrasound system.

The measurement principle of optical coherence tomography (OCT) is quite similar to US. However, light waves are used instead of sound waves. Thus, the measurement process needs to be performed at much higher speed and penetration depth is much lower than in the case of US. Most applications are in eye imaging where 3-D images of the eye are generated.