PET/CT
To my loving family.
Ronald Workman, Jr.

To the residents who have taught me what I know.
Ed Coleman
Foreword

*PET/CT: Essentials for Clinical Practice*, edited by Drs. Workman and Coleman, provides an introductory reference source for physicians who want to learn more about PET/CT, as well as for medical students and residents who are involved in the rapidly growing field of PET/CT.

The first two chapters of the text outline the basic principles involved in patient preparation, imaging interpretation, and reimbursement. The remainder of the text provides information necessary to make a learned and informed decision with regard to the appropriate use of PET/CT in oncologic, cardiac, and neurologic disorders.

An important factor in determining the value of any text is the knowledge and credentials of the editors. Dr. Coleman’s background as a leader in the fields of nuclear medicine, PET, PET/CT, and reimbursement places him at the forefront in the knowledge of the subject matter. Dr. Workman, having trained with Dr. Coleman, is eminently suited to co-edit a text of this nature.

*PET/CT: Essentials for Clinical Practice* is a well-written introductory text, and it provides fundamental information to improve understanding and clinical applications of this rapidly-evolving imaging modality.

The next decade will involve the field of functional/molecular imaging with a variety of innovative instrumentation developments, allowing us to examine smaller components of the human body with greater accuracy.

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PET and PET/CT have enjoyed tremendous growth in recent years. This growth has been fueled by the well-documented diagnostic accuracy of PET and PET/CT, particularly in oncologic applications. In an effort to mitigate potential growing pains, we have created this guide for you, the clinician, to aid in your understanding of this powerful and increasingly popular imaging modality.

Even at academic medical centers where PET was first introduced and heavily used, there are clinicians who are unfamiliar with the role of PET in their day-to-day practice. As nuclear medicine physicians and diagnostic radiologists who use this technology daily, we see it as our responsibility to educate all of our colleagues involved in patient care about PET and PET/CT. It is not our intention to create a full reference text on PET. Instead, we wish to provide a clinically oriented distillation of high-yield information in a portable and easy-to-use format. That is why we have written PET/CT: Essentials for Clinical Practice. We sincerely hope that you find this guide beneficial in your practice.

Ronald B. Workman, Jr., MD
R. Edward Coleman, MD
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Ronald B. Workman, Jr., MD
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1. Fundamentals of PET and PET/CT Imaging

Ronald B. Workman, Jr. and R. Edward Coleman

Brief History of Positron Emission Tomography

Positron emission tomography (PET) has been in existence since the 1970s due in large part to the pioneering work of Michael Phelps, PhD, Michel Ter-Pogossian, PhD, and others in the fields of medical physics and nuclear medicine [1]. Although initially a research tool, over the past 10 years PET has become increasingly used in the clinical setting, particularly after CMS (the Centers for Medicare and Medicaid Services, formerly known as the Health Care Financing Administration or HCFA) began reimbursing for PET evaluation of myocardial perfusion in 1995. Clinical utilization rose dramatically in 1998, when CMS began reimbursing for PET evaluation of solitary pulmonary nodules and initial staging of lung cancer. (CMS coverage as it relates to PET is covered in detail in Chapter 2.)

1998 also saw the creation of the first PET/computed tomography (CT) hybrid system, and in 2001, such systems became commercially available. Major manufacturers such as General Electric, Siemens, and Philips are now combining their latest CT technology with their latest PET technology to create very powerful hybrid systems that are the industry mainstay. PET/CT hybrids represent the state of the art in PET scanning, and it is estimated that PET/CT combination systems comprise 90% of sales in the current PET market [2]. The evolution of PET from its beginnings as an instrument of research to its present day wide and growing use in cancer, cardiac, and neurological imaging has resulted in instrumentation that is making a major impact in clinical care.

Before launching an in-depth discussion of the clinical applications of PET, it is important to describe the fundamental basic scientific principles behind nuclear medicine imaging, of which PET is a part.

Basics of Scintigraphy

In diagnostic nuclear medicine, radioactive substances, termed radiopharmaceuticals, are administered to patients and an image is obtained by placing the patient under a special scanner called a gamma camera. Such an image is properly termed a scintigram (from the Latin scintilla meaning spark or glimmer) and is generally referred to as a scan. Bone scans, ventilation/perfusion lung
scans, myocardial perfusion scans, thyroid scans, etc., are examples of commonly performed nuclear medicine studies. A radiopharmaceutical is a combination of a radioactive element, or radionuclide, and a pharmaceutical agent. In diagnostic imaging, this pharmaceutical molecule has a negligible pharmacologic effect because very small amounts are administered. Thus, the term radiotracer is sometimes used to describe these trace, but detectable, radioactive agents. Once the radiopharmaceutical has been administered, it is distributed within the patient according to its specific pharmacokinetics. Scintigraphic images are obtained by the gamma camera with the patient as the radioactive source.

The nuclear medicine imaging instrument is referred to as a gamma camera because its detection of photons, or gamma rays, generates the images. Gamma photons, sometimes denoted \( \gamma \), are packets of energy emitted by many radionuclides as they undergo decay. Technetium-99m (\(^{99m}\)Tc) is one example of a radionuclide that undergoes gamma decay, and it is the main radionuclide used in conventional nuclear medicine. \(^{99m}\)Tc can be coupled with a variety of pharmaceuticals to generate physiology-based images of many different organs and organ systems. At the heart of the gamma camera is the sodium iodide (NaI) crystal that absorbs the photons emitted by radionuclides such as \(^{99m}\)Tc. The crystal scintillates in response to absorbing a photon, and this scintillation event is converted into an electrical signal that is then processed to ultimately create an image.

The manner by which the gamma camera obtains an image also needs to be discussed. Planar imaging refers to flat, two-dimensional images. To generate a planar image, the gamma camera remains in one plane to collect the emitted photons and does not move, except to shift position as necessary within that same plane to obtain a complete image. An example of a planar image is the anterior view of a whole-body bone scan. Gamma cameras can also rotate around the patient, and with the use of computer-aided image reconstruction, generate tomographic images. This is referred to as SPECT, or single photon emission computed tomography. This technique is used in myocardial perfusion imaging, but can be employed in many other scenarios as well. Figure 1.1 shows a simple graphical representation of various image acquisition methods.

Figure 1.1. Examples of fundamental image acquisition methods. Planar, SPECT, and PET images are generated by emitted photons with the patient as the radiation source following radiopharmaceutical injection. CT images are generated by transmitted x-rays which have passed through the patient from an x-ray source. SPECT, PET, and CT generate tomographic images.
Not all radionuclides decay in the same way, and not all emitted gamma photons have the same energy. Some gamma photons are more energetic than others, and higher energy gamma rays must be imaged by instruments that are appropriately equipped to handle those energies. In addition to isomeric transition that produces gamma rays, there is alpha (α) decay and beta (β) decay in which highly energized particles are emitted from the nuclei of unstable nuclides. Alpha decay is not discussed in this book because it has no use in diagnostic imaging; however, beta decay is at the heart of positron emission tomography and is discussed in detail below.

Fundamentals of Positron Emission Tomography Imaging

PET is based on the physical properties of certain radioactive isotopes known as positron emitters. As their name implies, these radionuclides emit positrons rather than gamma photons when they undergo radioactive decay. Positron decay is a type of beta decay in which a positively charged particle, known as a beta+ particle (denoted β+), is emitted from a proton-rich nucleus as that nucleus attempts to become more stable. Although simplified, it is convenient and sufficient to think of a β+ particle as a positively charged electron. This simplification will aid in understanding later discussions concerning how a β+ interacts with matter. (A negatively charged beta particle, sometimes called a negatron, or β− particle, is identical to an electron except that its origin is the nucleus rather than the electron cloud surrounding the nucleus. β− particles do not play a role in PET.)

So do PET scanners image positrons? The answer is no. Unlike conventional nuclear medicine imaging with gamma-emitting radionuclides, the photons imaged in PET do not directly come from the nuclei that are undergoing decay. Nor are the positrons being imaged. Because positrons are particles that carry a positive charge, they travel only a very short distance, usually no more than a millimeter or two, before encountering a negatively charged electron. When a positron and electron collide, the particles are annihilated, and according to the conservation of matter and energy, the annihilation of the electron and positron results in the creation of two high energy gamma photons that travel approximately 180 degrees from one another (Figure 1.2). These high energy annihilation photons are not detected efficiently by a conventional gamma camera, and a specialized ring of detectors is used. Their simultaneous detection using short timing intervals is called coincident detection. Photon pairs that do not arrive at opposite points along the PET detector ring at the same time (within a few nanoseconds) are ignored by the PET scanner. This action is called discrimination and helps improve localization of true coincident events.

The energy of each coincident photon produced by the annihilation reaction is approximately 511 keV, which is much greater than the less energetic 140 keV photons emitted by 99mTc. PET detectors are specially engineered to handle these high energy photons, and because there is a ring of detectors, there is no need for the ring to rotate in order to obtain a tomographic image. Instead of