

Obtaining cardiac images from positron emission tomography, computed tomography, and magnetic resonance imaging: physical principles

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Abstract

Various imaging modalities are available to study the heart, including ultrasound, single photon emission computed tomography, positron emission tomography, computed tomography, and magnetic resonance imaging [1–4]. These modalities are fundamentally different and, consequently, different information is deduced from the images they generate. This paper describes briefly the physical principles of image generation with positron emission tomography, computed tomography, and magnetic resonance imaging.

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Introduction

Positron emission tomography (PET) is a molecular imaging technique used to obtain functional or physiological information on activities such as glucose metabolism, perfusion, and cardiac function. In contrast, computed tomography (CT) and magnetic resonance imaging (MRI) provide structural (anatomical) information and are used to study parameters such as myocardial wall thickness, heart function, wall motion, and stress, or are used for the purposes of angiography. The present paper will provide a short introduction to the physical principles of PET, CT, and MRI.

Positron emission tomography

Positron emission tomography is a molecular imaging technique that measures the distribution of a radioactive tracer in vivo [5]. This radiotracer (or radiopharmakon) is a molecule labeled with a positron-emitting radioactive atom, such as fluorine-18, carbon-11, or oxygen-15. When very small amounts (pico- or nanomoles) of a radiotracer are administered to a patient, the tracer distributes over and within the organs. The radioactive atom of the radiotracer emits positrons, which combine with electrons after traveling a distance up to several millimeters in tissue. Each positron and electron pair is then converted into two

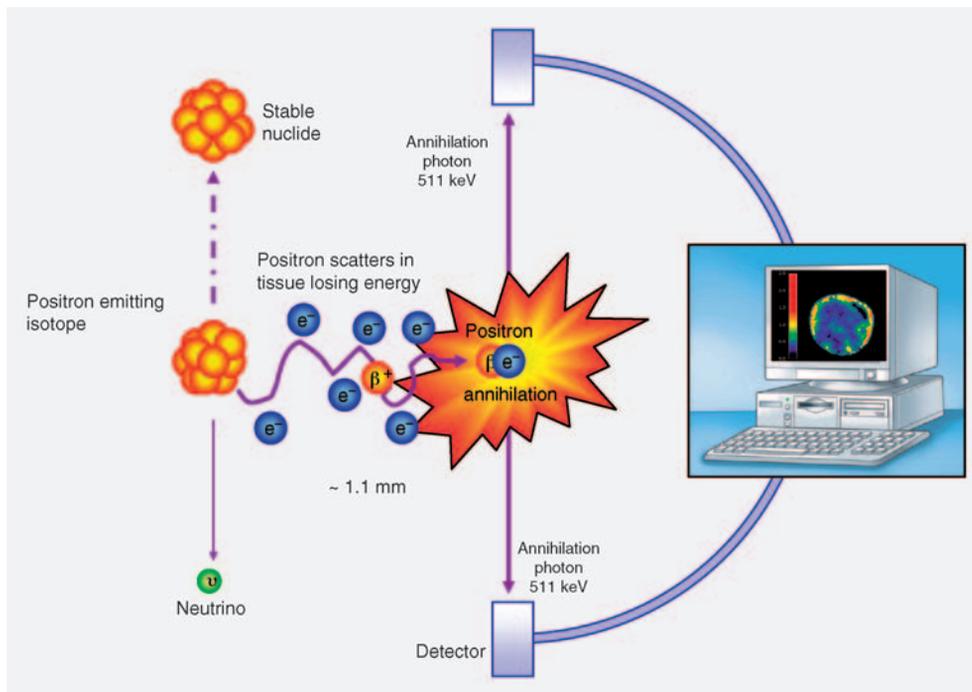


Figure 1. Principles of positron emission tomography image acquisition.

photons, each having an energy of 511 keV, and these are emitted in opposite directions. PET image acquisition is based on the simultaneous (coincidence) detection of these two photons.

A PET scanner consists of many photon detectors surrounding the patient. During a PET scan, millions of coincidence detections are collected, providing information about the distribution of the radiotracer in tissues. *Figure 1* demonstrates the principle of PET imaging. By making sequential images over time, it is possible to follow the uptake, retention, and washout of the tracer in tissue. This time course of the radiotracer or the distribution of a tracer at a certain period after its administration can be used to obtain functional (or physiological) information such as cardiac wall perfusion or glucose consumption [6–9].

Various radiotracers can be used to derive different physiological information concerning the heart. In *Table 1*, some commonly used radiotracers are listed, together with their clinical applicability.

Table 1. Examples of some commonly used (cardiac) positron emission tomography radiotracers and their application.

Tracer	Application
[¹⁸ F]-Fluorodeoxyglucose	Viability Cardiac function
Rubidium-82, [¹³ N]ammonia, [¹⁵ O]water	Perfusion
[¹¹ C]acetate	Oxygen consumption

Computed tomography

Computed tomography (CT) or computed axial tomography (CAT) measures the attenuation (absorption and scattering) of an X-ray photon beam through the patient, similar to X-ray imaging. In a CT system, an X-ray beam, generated using an X-ray tube, is rotated around the patient, providing information about photon attenuation through the patient from different angles (*Figure 2*). By combining measured attenuation profiles from these various angles it is possible to create a cross-sectional image of the distribution of attenuation coefficients. The attenuation coefficient indicates the amount of attenuation per centimeter of tissue, which for CT is expressed in Hounsfield units. Different tissue types (bone, blood, soft tissue, lungs) have different attenuation coefficients, and the measured distribution of these coefficients thus directly provides an anatomical cross-sectional image.

As the difference in attenuation coefficient between blood and tissue is relatively small, contrast agents are frequently used to enhance the signal in some of the tissues, for example in the blood pool. CT with contrast agents is frequently used to study coronary artery diseases (CT-based angiography), to derive detailed information on cardiac chamber volumes, or to localize myocardial regions with reduced perfusion.

By correlating CT image acquisition with the cardiac cycle using electrocardiograms (ECG triggering or gating), images of the various phases of the cardiac

Refresher corner

Physical principles of cardiac imaging

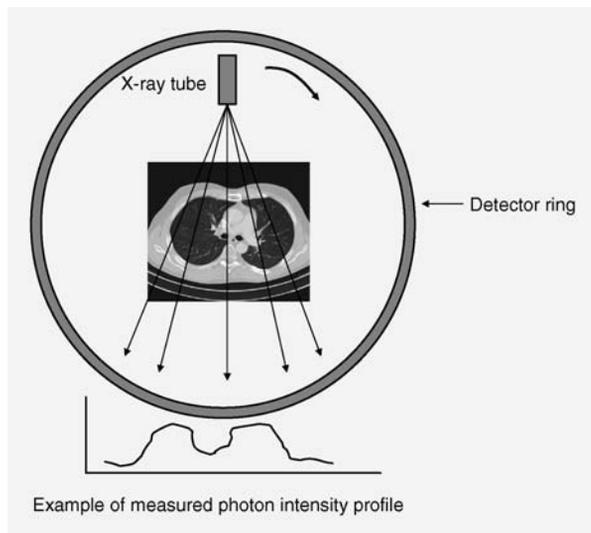


Figure 2. Principles of computed tomography image generation.

cycle can be collected, providing information on cardiac wall motion or to avoid motion artifacts (errors) on the CT images. Some common applications of cardiac CT imaging are listed in Table 2 [10–12].

Magnetic resonance imaging

Magnetic resonance imaging makes use of the magnetic moment of protons (situated in the nucleus of each atom) [13]. In MRI, it is mainly the protons of water molecules that give rise to a detectable signal. These protons have a positive charge and they ‘spin’ (rotate). This ‘rotating’ charge causes a magnetic dipole moment; thus protons can be considered as ‘mini-magnets’. When protons are placed in a strong external magnetic field, the magnetic dipoles are aligned (parallel or antiparallel) with the external field (Figure 3). By using a radiofrequency wave, the magnetic dipoles can be ‘flipped’ into a plane transverse to the direction of the magnetic field.

An MRI scanner uses a strong magnetic field, radiofrequency pulses to generate the signal, and receiver coils to measure the signal from the precession of the magnetic dipoles (Figure 3). The ‘speed’ of precession of the magnetic moment depends on the strength of the external magnetic field. Therefore, by varying the

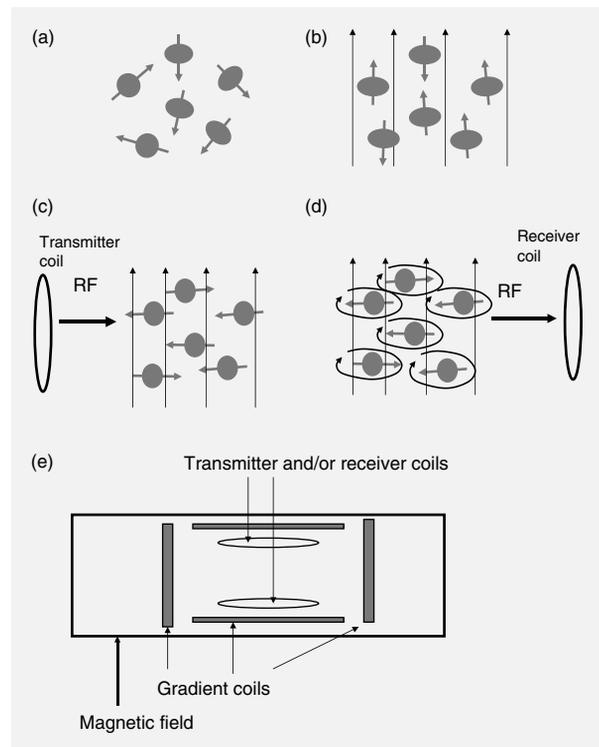


Figure 3. (a) Illustration of random direction of magnetic dipole moments in absence of external magnetic field. (b) Alignment (parallel or antiparallel) of magnetic dipole moments in the presence of an external magnetic field. A (small) preference for parallel alignment exists, depending on field strength. (c) Use of a radiofrequency (RF) pulse to ‘flip’ magnetic dipole moments into the transverse plane. The RF pulse is generated using a transmitter coil. (d) Precession of magnetic dipoles within the transverse plane. Measurement of the RF signal caused by the precession using a receiver coil. (e) Schematic drawing of the main components of an magnetic resonance imaging scanner.

strength of the external magnetic field within the MRI scanner (using field gradients), it is possible to make the frequency of the precession (Larmor frequency) become position-dependent, and it can then be used for purposes of localization.

Signals coming from the precession of the magnetic moments do not last forever, but decrease over time as a result of realignment of the dipole moment with the external magnetic field (referred to as ‘T1 relaxation’) or because precessions are no longer synchronized (T2 or T2* relaxation). By using various imaging techniques (sequences), an MRI scanner is able to

Table II. Examples of cardiac computed tomography (CT) applications and basic information derived from the CT image.

Application	Information obtained from the CT image
Cardiomyopathy	(Changes in) myocardium thickness
Atherosclerosis	Calcification of coronary arteries
Angiography	Use of contrast agents to visualize arteries and to detect coronary artery stenosis
Cardiac function	Electrocardiogram-gated CT acquisition to derive CT images over the various phases of the cardiac cycle, used to study wall motion and cardiac function

Table III. Some applications of cardiac magnetic resonance imaging.

Applications	Information obtained the from the magnetic resonance (MR) image
Cardiomyopathy	Assessment of cardiac wall thickness
Cardiac function	Electrocardiogram-triggered (or phase-encoded) acquisition obtains MR image of the various phases of the cardiac cycle. Data provide direct information on cardiac wall motion and cardiac function
Perfusion (qualitative)	Uses first-pass information after bolus administration of a contrast agent (eg, gadolinium-DTPA). Recently, perfusion has begun to be evaluated using delayed enhancement imaging based on delayed uptake of contrast agent and washout in myocardial scar tissue
DTPA, diethylene triamino pentacetic acid	

emphasize different causes of signal loss separately (T1- and T2-weighted MRI scans). As various tissue types have different T1 and T2 relaxation times, an MRI scanner is able to distinguish various tissues, thereby generating anatomical images with very high spatial resolution (sharp images with high contrast).

To summarize, variation of precession or Larmor frequency of the magnetic moments as a result of magnetic field gradients is used for position encoding (localization), whereas differences in T1 and T2 relaxation times are used for tissue differentiation.

In MRI technology, similar to CT, contrast agents are available to improve the contrast between various tissue types or to enhance the signal from, for example, the blood pool. Contrast is obtained by the change in relaxation times of water as a result of the presence of the agent. One application in which such a contrast agent is used is the assessment of myocardial perfusion, although quantitative assessment of cardiac perfusion is not yet possible [14,15]. Finally, ECG triggering (or phase encoding) performs acquisition of MRI images over the various phases of the cardiac cycle, allowing assessment of cardiac function (Table 3).

Structural versus functional (molecular) imaging

As explained above, CT and MRI provide detailed anatomical information, as opposed to PET, which can provide functional or molecular images (Table 4).

CT and MRI are not (yet) able to provide quantitative hemodynamic or metabolic information. To assess perfusion quantitatively or to assess metabolic processes, PET is the method of choice. Recently, combined PET/CT systems have become available that allow the simultaneous acquisition of both structural and physiological information [16,17]. Integrated anatomical and functional (molecular) imaging seems very promising, and its potential additional clinical value will be assessed in the near future [16].

Limitations of current overview

The purpose of this paper was to present a short introduction to the physical principles of image acquisition with PET, CT, and MRI. Sophisticated CT and MRI scanning techniques, such as MRI tagging, have not been addressed and are beyond the scope of this paper. Moreover a short, but not complete, list of some of the main applications of these imaging techniques is given. Interested readers are encouraged to read the review and educational papers listed in the reference list for a more detailed description of the physical principles of the imaging modalities [5,12,13].

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Table IV. Physical principles of image generation.

Modality	Type of information collected	Basic principle
Positron emission tomography (PET)	Functional (physiological)	Measurement of distribution of positron-emitting radioactive tracer
Computed tomography (CT)	Structural or anatomical	CT scanner measures distribution of attenuation coefficients
Magnetic resonance imaging (MRI)	Structural or anatomical	MRI scanner measures (relaxation of) precession of magnetic dipole moments of protons of (mainly) water molecules

Refresher corner

Physical principles of cardiac imaging

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