Cardiovascular PET/MRI

Challenges and Opportunities

Richard LaForest, PhD, Pamela K. Woodard, MD, Robert J. Gropler, MD*

KEYWORDS

• Positron Emission Tomography (PET) • Magnetic Resonance Imaging (MRI) • PET/MRI • Cardiovascular • Myocardium • Atherosclerosis

KEY POINTS

- The main advantages of PET/MRI over PET/computed tomography (CT) are the improved soft tissue contrast with MRI obtained without ionizing radiation and the potential for simultaneous acquisition of the PET and magnetic resonance images.
- The complexity of PET/MRI poses some significant technical challenges, which can be broadly characterized as accurate attenuation measurement, motion correction, and streamlining laboratory workflow.
- Clinical acceptance of PET/MRI requires the identification of clinical scenarios in which it has been found that simultaneously acquired information from PET and MRI is required.
- Numerous potential scenarios exist, including combined coronary angiography with measurements of perfusion and function and detection of atherosclerotic plaque and various myocardial diseases.
- Success of PET/MRI will depend in large part on the development of molecular imaging probes that exploit its strengths.

INTRODUCTION

Since its introduction in the early 2000, the hybridization of PET/CT has revolutionized medical imaging by the juxtaposition of functional PET images with high-resolution anatomic CT images. In the clinical setting, this colocalizing capability has been primarily exploited for oncologic purposes in which accurate attribution of biological activity specifically to tumor is of critical importance. In contrast, the colocalization capabilities of PET/CT have not been used to a large extent in cardiovascular (CV) disease, with CT attenuation correction of the PET images being the notable exception. This lack of use is the result of several factors, including the dearth of clinical indications in which the in-depth anatomic information afforded by CT is needed relative to the PET images (and vice versa), the complexities imparted by cardiac and respiratory motion on accurate colocalization, the logistical challenges to laboratory work flow imposed by sequential acquisition of the PET and CT images, and concerns for the risks associated with exposure to low-dose γ radiation and intravenous contrast.

More recently, systems combining PET and MRI have appeared on the market. The 2 main advantages of these systems over PET/CT are the improved soft tissue contrast with MRI obtained without ionizing radiation and the potential for simultaneous acquisition of the PET and MRI. However, its clinical acceptance has been slow for several reasons. Most notable is the high price of these systems in an environment in which reimbursement for using the technology is unclear. The

Conflict of Interest: Washington University has a Biograph mMR System and a Research Agreement with Siemens.
Mallinckrodt Institute of Radiology, Washington University School of Medicine, 4525 Scott Avenue, Suite 1307, St Louis, MO 63110, USA
* Corresponding author.
E-mail address: Groplerr@mir.wustl.edu

Cardiol Clin 34 (2016) 25–35
http://dx.doi.org/10.1016/j.ccl.2015.08.002
0733-8651/16/$ – see front matter

latter reflects the lack of evidence supporting the notion that key clinical information obtained with the simultaneous acquisition of PET and MRI data sets could not be acquired on separate PET and MR examinations. Moreover, significant technical challenges must be overcome from an image acquisition, processing, display, and laboratory workflow perspective for implementing CV PET/MRI on a routine clinical basis. However, the potential is high for PET/MRI to become an important tool in the treatment of the patient with CV disease. This review highlights this potential by discussing the current advantages of MRI versus CT and PET/MRI, the technical challenges in performing PET/MRI and incorporating it into laboratory workflow, and potential clinical scenarios in which PET/MRI might be beneficial in the context of CV imaging.

WHY PET/MRI?

The impetus for the development of PET/MRI reflected the relative advantages of MRI compared with CT (summarized in **Table 1**). Two key advantages for MRI over CT are the higher soft tissue contrast and the lack of radiation reduction exposure to the patient. Although for many applications, such as attenuation correction and coronary angiography, radiation strategies have been used.[1,2] Conversely, the use of electromagnetic fields in MRI generally precludes the imaging of patients with mechanical heart valves, pacemakers, or implantable cardioverter/defibrillators (ICDs). Thus, CT is of critical importance in the treatment of these patients. With respect to the assessment of left ventricular (LV) morphology and function, MRI is considered the gold standard, providing accurate and detailed measurements of LV mass, volume, regional, and global systolic function. Although CT can perform many of these measurements, they come at the cost of significant radiation exposure. Because of its ease of use and speed, CT is widely used for the noninvasive performance of coronary angiography. Moreover, as mentioned above, dose reduction strategies have significantly reduced radiation exposure. Although considerable progress continues for MR angiography, technical challenges still remain, such as the detrimental effects of cardiac, respiratory, and patient motion on image quality and solving the conundrum of attaining high spatial resolution while retaining adequate vessel-to-tissue contrast and signal-to-noise ratio all within an acceptable scanning time. Both MRI and CT require the use of intravenous contrast to enhance imaging for certain applications, however, MRI agents have a better side-effect profile compared with the iodinated CT contrast agents.[3] Moreover, many MRI measurements such as myocardial perfusion (eg, arterial spin labeling) and coronary angiography can be performed without contrast.[4,5] Characterization of tissue properties such as myocardial fiber orientation, the presence of extracellular water, cellular metabolism, and lipid content are possible with various MRI and spectroscopic techniques.[6–9] Tissue characterization with CT is much more limited because the imaging signal is based on differences in x-ray attenuation. Both MRI- and CT-based molecular imaging agents have been developed, with sensitivity being slightly better for MRI ($\sim 10^{-5}$ M) compared with CT ($\sim 10^{-3}$ M). Of note, sensitivity is significantly lower than what can be achieved with PET (10^{-11} to 10^{-12} M).[10] Imaging is faster and easier to perform with CT compared with MRI, which results in higher patent satisfaction and compliance. In addition, the greater complexity of MRI protocols requires greater involvement of highly trained personnel.

Table 1
Relative merits of CT and MRI

Consideration	CT	MRI
Soft tissue contrast	No	Yes
Ionizing radiation	Yes	No
Electromagnetic field	No	Yes
LV structure and function	Fair	Excellent
Angiography	Excellent	Fair
Risk of contrast agents	Low	Very low
Tissue characterization	Low	Excellent
Potential for molecular imaging	Fair	Moderate
Patient comfort	Excellent	Fair

PET/MRI SYSTEMS

Numerous PET/MRI designs have been explored including separate PET and MRI systems connected by an integrated bed system and, more recently, fully integrated PET/MRI systems. The technical specifications and performance characteristics of these systems have been comprehensively reviewed and are be detailed here.[11,12] Most recent development efforts have focused on integrated PET/MRI systems that permit simultaneous (or at least combined) acquisition of all imaging data. To integrate PET into an MRI system, a solution had to be devised to replace photomultiplier tubes, which provide the light read-out of a scintillation event in PET but do not operate in magnetic field because of the action of the Lorentz