A Stepping-Stone to Fully Integrated Whole-Body PET/MRI

Ciprian Catana

Massachusetts General Hospital and Harvard Medical School, Charlestown, Massachusetts

PET and MRI have long been used to obtain molecular, functional, and morphologic information to study the human body in health and disease. In addition to allowing the simultaneous acquisition of these complementary datasets, fully integrated PET/MRI systems have the potential to combine their strengths and alleviate many of their limitations. Although the initial efforts to combine these 2 imaging modalities were made in the preclinical arena in the 1990s (*1*), it took almost a decade for the major medical equipment manufacturers to recognize the potential of this emerging field. The first prototype device developed for human use allowed the simultaneous examination of the brain (*2*). This prototype was followed by the introduction in 2010 of the first fully integrated whole-body PET/MRI system, called the Biograph mMR (Siemens Healthineers). The results of the performance characterization measurements for this scanner were reported by Delso et al. in *The Journal of Nuclear Medicine* the following year (*3*).

At first sight, the article by Delso et al. (*3*) is similar to other papers reporting the initial results obtained with a novel imaging system. However, a careful analysis reveals, with the benefit of hindsight, that this paper was distinctive in many ways and managed to highlight the requirements for progress in the field and forecast some of the challenges it has faced over the last decade. Starting with the list of authors, the need for close collaboration between academia and industry, nuclear medicine and radiology, and physicians and physicists was emphasized. The methods section still serves as a blueprint for the types of studies that need to be performed for characterizing the performance of each of the components of a hybrid device within the constraints imposed by the other modality. As one example, assessing the PET image quality using standard phantoms required a calculated attenuation map as the MR-based methods specifically developed for human imaging were not adequate for this purpose. Although substantial progress has been made and correct human attenuation maps can

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For correspondence or reprints contact: Ciprian Catana, Athinoula A. Martinos Center for Biomedical Imaging, Massachusetts General Hospital and Harvard Medical School, 13th St., Building 149, Room 2301, Charlestown, MA 02129.

E-mail: ccatana@mgh.harvard.edu

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Performance Measurements of the Siemens mMR Integrated Whole-Body PET/MR Scanner

Gaspar Delso*[1], Sebastian Fürst*[1], Björn Jakoby[2-4], Ralf Ladebeck[5], Carl Ganter[6], Stephan G. Nekolla[1], Markus Schwaiger[1], and Sibylle I. Ziegler[1]

[1]Nuklearmedizin, Klinikum Rechts der Isar, Technische Universität München, München, Germany; [2]University of Surrey, Guildford, United Kingdom; [3]University of Tennessee Medical Center, Knoxville, Tennessee; [4]Siemens Medical Solutions USA, Inc., Knoxville, Tennessee; [5]Siemens Healthcare, Erlangen, Germany; and [6]Institut für Radiologie, Klinikum Rechts der Isar, Technische Universität München, München, Germany

The recently released Biograph mMR is the first commercially available integrated whole-body PET/MR scanner. There are considerable advantages to integrating both modalities in a single scanner that enables truly simultaneous acquisition. However, there are also concerns about the possible degradation of both PET and MR performance in an integrated system. This paper evaluates the performance of the Biograph mMR during independent and simultaneous acquisition of PET and morphologic MR data. **Methods:** The NEMA NU 2-2007 protocol was followed for studying the PET performance. The following measurements were performed: spatial resolution; scatter fraction, count losses, and randoms; sensitivity; accuracy of the correction for count losses and randoms; and image quality. The quality control manual of the American College of Radiology was followed for studying the MR performance. The following measurements were performed: geometric accuracy, spatial resolution, low-contrast detectability, signal-to-noise ratio, static field (B_0) homogeneity, radiofrequency field (B_1) homogeneity, and radiofrequency noise. **Results:** An average spatial resolution of 4.3 mm in full width at half maximum was measured at 1 cm offset from the center of the field of view. The system sensitivity was 15.0 kcps/MBq along the center of the scanner. The scatter fraction was 37.9%, and the peak noise-equivalent count rate was 184 kcps at 23.1 kBq/mL. The maximum absolute value of the relative count rate error due to dead-time losses and randoms was 5.5%. The average residual error in scatter and attenuation correction was 12.1%. All MR parameters were within the tolerances defined by the American College of Radiology. B_0 inhomogeneities below 1 ppm were measured in a 120-mm radius. B_1 homogeneity and signal-to-sary to evaluate the more advanced MR applications, such as functional imaging and spectroscopy.

Key Words: PET/MR; NEMA; performance

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The potential of multimodal imaging for improved noninvasive tissue characterization has been recognized in clinical and preclinical applications (*1*). This potential is reflected in the extensive research effort dedicated to software coregistration in the 1990s and the immediate success of combined PET/CT scanners after their introduction in the early 2000s (*2*).

Combining the high soft-tissue contrast of MR and molecular signals from PET may provide further multimodal assessment, reaching beyond the anatomic correlation by introducing functional MR as well. There are considerable advantages to integrating these modalities in a single scanner (*3*). The possibility of truly simultaneous operation allows the acquisition of several MR sequences during the PET scan, without increasing the examination time. Additionally, the radiation exposure is reduced if CT is not necessary.

The combination of MR and PET scanners is highly challenging. The high static magnetic field, quickly changing

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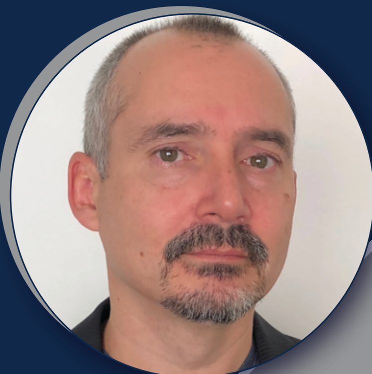

now be generated for most body parts, phantom imaging is still challenging a decade later. From a technical point of view, the results presented confirmed that the hardware of PET and MRI components can be successfully integrated and that their performance is on a par with that of stand-alone devices. This confirmation was particularly relevant on the PET side, as the Biograph mMR was the first commercial system to use semiconductor-based photon detectors (i.e., avalanche photodiodes) as a replacement for photomultiplier tubes, which, until then, were used in virtually all commercially available PET/CT scanners. This advance arguably opened the road to the subsequent adoption of an even more advanced semiconductor-based photon detector technology (i.e., silicon photomultipliers) in PET/CT (*4*) and in latest-generation PET/MRI scanners (*5*). Finally, although only 2 proof-of-principle human studies were presented, this first technical report enabled clinicians to subsequently focus on assessing the clinical potential of this novel technology. In fact, the results of a comparison between PET/CT and PET/MRI in oncologic patients were reported by the same group in another highly cited paper published the following year (*6*).

As of July 2020, the paper by Delso et al. (*3*) had been cited more than 500 times by authors from more than 25 countries, proving its far-reaching influence. Furthermore, attesting to its multidisciplinary impact, the citing papers belong to a wide range of scientific areas (e.g., physics, chemistry, mathematics, engineering, and computer science) and clinical areas (e.g., radiology and nuclear medicine, oncology, cardiology, neuroscience, pediatrics, hematology, endocrinology, and gastroenterology). Remarkably, the Hirsch index (a measurement of the impact of a particular scientist rather than a journal) of this paper, which continues to be cited, is currently 50, with many of the citing papers having reached in turn the ‘‘highly cited’’ status in their fields. Although 3 imaging equipment manufacturers are currently commercializing fully integrated PET/MRI systems for human use, the clinical adoption of PET/MRI has been much slower than that of PET/CT, with only approximately 250 systems being operational around the world a decade after its introduction. The exact role of PET/MRI within our health-care system is being explored for routine and advanced applications in oncology, neurology, and cardiology. PET/MRI could also enable several recent developments from the research arena (e.g., improved quantification enabled by MR-assisted PET data optimization, machine learning applied to multimodal datasets, and precision medicine informed by molecular imaging) to soon become clinical reality.

Just as the Biograph mMR marked the evolution of PET/MRI hardware from the prototype phase to the product phase, the report by Delso et al. (*3*) paved the way toward fully integrated PET/MRI investigations and served as the technical validation that facilitated the transition of this field from the research arena to the clinical arena. In addition to its substantial impact on nuclear medicine and radiology, this paper contributed to the wider embracing of these imaging modalities by other areas of medicine.

DISCLOSURE

No potential conflict of interest relevant to this article was reported.

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to be performed using calculated attenuation maps, because the method to obtain MR-based attenuation maps (a 4-compartment tissue classification based on a Dixon sequence) is optimized for human imaging and not well suited for phantom studies. The system includes a 2-compartment mode, but this is a solution for only phantoms in which the Dixon sequence yields appropriate images, such as the solid germanium phantom used for the daily quality control. In the case of the NEMA image-quality phantom, dielectric resonance artifacts prevented the use of this method. Future developments will need to include more flexible methods of using various MR sequences or predefined maps for attenuation correction.

In summary, the overall performance of the PET sub-system is competitive with state-of-the-art photomultiplier tube–based systems, showing for what is to our knowledge the first time the great potential of semiconductor-based detectors in clinical whole-body PET. Further work is under way to evaluate those aspects not covered by the NEMA protocol, such as the impact of attenuation map truncation.

Concerning the MR subsystem, no significant inhomoge-neities have been detected in either the static or the radio-frequency fields. The operation of the PET detector inside the MR bore and the transmission of data to the external processing units introduce no visible interference in the MR operating band. The ACR quality control measurements show a performance practically identical to that of the Verio.

Further work is required to test the performance of the scanner in a larger area of the FOV. Of particular interest will be the study of inhomogeneities and distortion toward the edges of the FOV and their possible impact on the calculation of MR-based attenuation maps.

CONCLUSION

The performance of the Siemens mMR whole-body PET/MR scanner has been evaluated following the NEMA NU 2-2007 protocol and ACR quality control manual. The results compare favorably with state-of-the-art PET/CT scanners. This study indicates the successful integration of new detector technology in PET/MR for whole-body imaging. However, further work is necessary to evaluate the more advanced MR applications, such as functional imaging and spectroscopy.

DISCLOSURE STATEMENT

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