Radiology

Global Trends in Hybrid Imaging[1]

Hedvig Hricak, MD, PhD, Dr(hc)
Byung Ihn Choi, MD, PhD
Andrew M. Scott, MD
Kazuro Sugimura, MD, PhD
Ada Muellner, MS
Gustav K. von Schulthess, MD, PhD
Maximilian F. Reiser, MD, Dr(hc)
Michael M. Graham, MD, PhD
N. Reed Dunnick, MD
Steven M. Larson, MD

At the 2009 Scientific Assembly and Annual Meeting of the Radiological Society of North America, a special session was devoted to global trends in hybrid imaging. This article expands on the key points of the session, focusing primarily on positron emission tomography/computed tomography. Global trends in hybrid imaging equipment acquisition, usage, and image interpretation practices are reviewed, and emerging requirements for training and clinical privileging are discussed. Also considered are the current benefits of hybrid imaging for patient care and workflow and the potential of hybrid imaging for advancing drug development and personalized medicine.

Supplemental material: *http://radiology.rsna.org/lookup/suppl/doi:10.1148/radiol.10100579/-/DC1*

[1] From the Department of Radiology, Memorial Sloan-Kettering Cancer Center, 1275 York Avenue, Room C-278, New York, NY 10065 (H.H., A.M., S.M.L.); Department of Radiology and Institute of Radiation Medicine, Seoul National University Hospital, Seoul, Korea (B.I.C.); Centre for PET, Ludwig Institute for Cancer Research, Heidelberg, Victoria, Australia (A.M.S.); Department of Radiology, Kobe University Graduate School of Medicine, Kobe, Japan (K.S.); Department of Medical Radiology, University Hospital of Zurich, Zurich, Switzerland (G.K.v.S.); Departments of Radiology and Nuclear Medicine, Ludwig Maximilian University, Munich, Germany (M.F.R.); Department of Radiology, University of Iowa, Iowa City, Iowa (M.M.G.); and Radiology Department, University of Michigan Medical Center, Ann Arbor, Mich (N.R.D.). Received March 18, 2010; revision requested April 14; revision received June 8; accepted June 9; final version accepted June 15. **Address correspondence to** A.M. (e-mail: *muellnea@mskcc.org*).

The 2009 Scientific Assembly and Annual Meeting of the Radiological Society of North America featured a special session on global trends in hybrid imaging. The purpose of the meeting was to chart trends in the acquisition and use of hybrid imaging equipment around the world and to discuss shared concerns relating to hybrid imaging. This article presents and expands on the key points addressed during the session, which was attended by more than 30 radiology and nuclear medicine leaders from national societies around the world (Appendix E1 [online]).

Hybrid imaging is defined as the fusion of two or more imaging technologies into a single, new form of imaging. Typically, this new form is synergistic—that is, more powerful than the sum of its parts. Although some hybrid imaging modalities may be used purely to depict anatomy, the most exciting characteristic of hybrid imaging is its potential to show molecular processes in vivo within their larger anatomic context. Hybrid imaging modalities now in existence include ultrasonography (US)/ magnetic resonance (MR) imaging, MR imaging/angiography, computed tomography (CT)/angiography, single photon emission computed tomography (SPECT)/ CT, positron emission tomography (PET)/ CT, and, though it is not yet commercially available, PET/MR imaging. Most of these have the potential to aid the development of personalized, molecular medicine.

To realize the full potential of hybrid imaging, diverse kinds of clinical and technical expertise must be brought together. Because the use of PET/CT is growing more rapidly than that of any other hybrid imaging technique, it is particularly important for diagnostic radiologists and nuclear medicine physicians to establish new pathways of collaboration within institutions, nationally and internationally. Issues they must jointly confront include when to use hybrid imaging; how to ensure quality imaging and optimal, clinically relevant interpretation; and how best to train and provide credentials in hybrid imaging for future and already practicing physicians, technologists, and other health care professionals. Furthermore, recognizing that globalization is inevitable, leaders in both specialties must work toward global standardization of hybrid imaging to promote rapid exchange of information in preclinical research, clinical trials, and patient care.

This report focuses primarily on PET/CT because of its rapidly growing prominence. Data are presented on global trends in equipment acquisition, usage, and image interpretation. The benefits of hybrid imaging for patient care and workflow are discussed, as are emerging requirements for training and privileging (unless otherwise noted, the opinions offered represent those of the authors only). Furthermore, because "today's research is tomorrow's practice" (1), attention is given to the importance of hybrid imaging for advancing the emerging field of molecular imaging.

Hybrid Imaging: A Vital Tool for Molecular Imaging and Personalized Medicine

Molecular imaging has become an important tool for preclinical as well as clinical research across a broad span of disciplines, including oncology, cardiology, neurology, psychiatry, and pharmacology. Molecular imaging shows particular promise as a means to accelerate the transfer of laboratory discoveries into clinical practice and the implementation of personalized, molecularly targeted medicine.

Molecular imaging can be performed with many different modalities, including CT, MR imaging, MR spectroscopic imaging, US, SPECT, PET, and optical imaging. Except for diffusion-weighted MR imaging and MR spectroscopic imaging, which image water molecules and metabolites, respectively, all molecular imaging techniques depend on the use of exogenous probes to provide imaging signal or contrast. The probes typically consist of an "affinity" component that interacts with the target and a "signaling" component that provides image contrast. While radiolabeled probes are used for PET or SPECT, the signaling component can be a fluorochrome in optical imaging or a chelate containing a paramagnetic atom in MR imaging. Regardless of their composition, molecular imaging probes are designed to make visible the specific properties that distinguish normal from pathologic tissue.

Of the available molecular imaging techniques, PET is at present the most powerful and versatile. Not only do the special physics of PET imaging make it exquisitely sensitive and quantitative, but the broad range of available positron-emitting radionuclides (eg, fluorine 18 [^{18}F], carbon 11 [^{11}C], nitrogen 13, iodine 124 [^{124}I], copper 64 [^{64}Cu], gallium 68 [^{68}Ga], and zirconium 89) allows the power of the tracer principle to be extended into research and discovery that is relevant to much of human illness and to drug development. Essential to the development and implementation of new tracers—and thus to the progress of molecular imaging—is extensive testing of tracers' biodistribution and biosafety, a process that requires a team effort. As new tracers enter clinical evaluation, the use of hybrid devices that combine nuclear medicine and anatomic imaging becomes essential. Therefore, the future of molecular imaging will depend on the availability of radiation chemists, radiation pharmacists, and nuclear physicists, as well as physicians whose training combines nuclear medicine, molecular biology,

Published online before print
10.1148/radiol.10100579

Radiology 2010; 257:498–506

Abbreviations:
EANM = European Association of Nuclear Medicine
ESR = European Society of Radiology
FDG = fluorodeoxyglucose

Author contributions:
Guarantors of integrity of entire study, H.H., B.C., K.S.; study concepts/study design or data acquisition or data analysis/interpretation, all authors; manuscript drafting or manuscript revision for important intellectual content, all authors; manuscript final version approval, all authors; literature research, A.S., A.M., M.F.R., N.R.D., S.M.L.; clinical studies, A.S., K.S., M.F.R.; statistical analysis, A.S.; and manuscript editing, H.H., B.C., A.S., K.S., A.M., G.K.v.S., N.R.D., S.M.L.

Authors stated no financial relationship to disclose.

and diagnostic radiology. It is essential to foster a strong working relationship between the nuclear medicine and radiology communities, so that knowledge from both specialties can be combined in a rich matrix that supports continuous innovation and optimal patient care.

Although hybrid PET/CT already has a number of important clinical applications, many more are expected to come to light over the next decade. Increased PET/CT usage is expected to stem not only from greater usage of ^{18}F fluorodeoxyglucose (FDG) but also from the introduction of an armamentarium of new radiotracers that will enable disclosure of previously hidden properties of human diseases and offer "road maps" for patient therapy and disease management. Promising new PET tracers now range from metabolic substrates, hypoxia agents, neurotransporters, and drugs that exploit the distinctive intermediary metabolism of normal and pathologic tissue function to monoclonal antibodies, peptides, and molecules that have exquisite specificity for detecting surface and subsurface molecules expressed in disease processes. At research centers around the world, the numbers of radiolabeled tracers used for patient care are growing. For example, from 2005 to 2008 at the Ludwig Maximilian University in Munich, Germany, the percentage of all PET and PET/CT studies performed annually with ^{18}F-FDG decreased from 93% to 73%, while the total number of radiolabeled tracers in use increased from three to nine. The Table lists some of the radiotracers that are now being used in clinical research programs around the world. It shows a number of tracers used globally in spite of a lack of commercial availability.

Although oncology dominates the use of PET imaging, applications for molecular imaging are also increasing in other fields. In a recent survey of European Association of Nuclear Medicine (EANM) members (2), 60%, 54%, and 40% of respondents reported that their institutions used PET or PET/CT for applications in neurology, infection and/or inflammation, and cardiology, respectively. In these fields, as in oncology, new PET tracers are expected to change the ways disease processes are understood and managed. For example, recent research (3,4) has shown that PET imaging in patients with dementia with amyloid plaque or receptor ligands can help detect some cases of dementia earlier than MR imaging, FDG PET, or conventional neurologic testing. In many countries, growing numbers of neurologists, cardiologists, and oncologists are cross training in nuclear medicine, because they recognize the potential of PET/CT imaging and theranostics to dramatically improve patient care.

Examples of PET Radiotracers Used in Clinical Trials

Radiotracer	Function or Molecular Target
Phenotypic probe	
^{18}F-FDG	Glycolysis
^{11}C-methionine	Amino acid transport
^{18}F-fluorocyclobutane-1-carboxylic acid	Amino acid transport
^{18}F-fluoro-L-thymidine	Cell proliferation
^{18}F-fluorodihydrotestosterone	Androgen receptor
^{18}F-fluoroestradiol	Estrogen receptor
Sodium ^{124}I	Sodium iodide symporter
^{11}C acetate	Krebs cycle, fatty acid synthesis
^{18}F-fluoromisonidazole	Hypoxia
Targeted probe	
^{68}Ga-Fab'2 Herceptin	HER2
^{124}I-cG250	Carbonic anhydrase IX
^{124}I-A33	A33 antigen
^{124}I-3F8	GD2
^{64}Cu-Herceptin	HER2
Reporter gene imaging probe	
^{124}I-2'-fluoro-2'-deoxy-1-β-D-arabinofuranosyl-5-iodouracil	Thymidine kinase (herpes virus)

Global Equipment Distribution and Use

Trends in equipment acquisition and distribution confirm that PET/CT has been globally accepted as a vitally important clinical imaging tool and a valuable improvement over stand-alone PET. Today, the highest concentrations of PET and PET/CT units per capita are in the United States (approximately 4 units per million inhabitants) and Japan (approximately 3 units per million inhabitants), followed by Belgium, Luxembourg, Denmark, and Switzerland (each with approximately 2 units per million inhabitants). Austria, the Netherlands, Italy, and South Korea have between 1.5 and 2.0 units per million inhabitants (2,5–10).

In the past 5 years, installations of hybrid PET/CT systems have virtually supplanted those of stand-alone PET scanners (11,12). This trend has been observed globally (Fig 1), and many major equipment manufacturers no longer offer stand-alone PET scanners. Thus, the prevalence of stand-alone PET scanners in individual countries is strongly linked to the timing of PET installation, with countries that have only recently implemented PET having PET/CT systems almost exclusively. A trend toward the incorporation of high-end multisection CT scanners in PET/CT systems has also been observed (11,12).

From 2001 to 2008, the percentage of PET units installed per year in the United States that were stand-alone PET scanners fell from 60% to 0% (6). By 2008, stand-alone PET units accounted for only 26% of all fixed PET units in the United States. Concordantly, from 2005 to 2008, the percentage of PET studies performed by using stand-alone PET dropped from 30% to 13% (Fig 2) (6).

Overall, in the United States, the usage of PET and PET/CT has grown

Figure 1

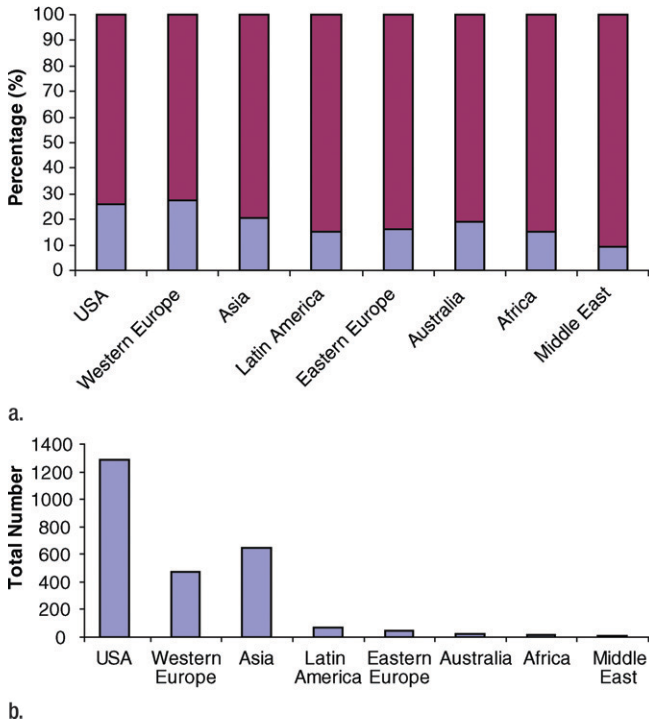

Figure 1: Bar graphs show **(a)** percentages of stand-alone PET scanners (blue bars) versus percentages of PET/CT scanners (purple bars) worldwide and **(b)** total numbers of PET and PET/CT scanners worldwide (5,6,9,10). Data also provided by Maurizio Dondi, MD, PhD, International Atomic Energy Agency, Vienna, Austria, in February 2010, on the basis of surveys from 2009.

Figure 2

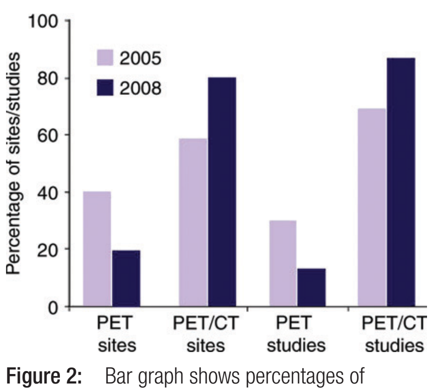

Figure 2: Bar graph shows percentages of PET-only sites and studies versus PET/CT sites and studies in the United States, 2005–2008 (6).

at a remarkable pace in the past 5 years. Surveys conducted by the market research firm IMV (Greenbelt, Md) showed an average annual increase of 10.4% in the number of patient studies performed from 2005 to 2008 at PET and PET/CT sites in the United States (6). However, the growth rate has been slowing somewhat, and from 2007 to 2008, the total number of PET and PET/CT patient studies increased by only 4%, from 1.48 million to 1.52 million (6).

In the United States, ownership of PET and PET/CT scanners by nonradiologists is increasing quickly. Using Medicare data, Agarwal et al (13) found that from 2002 to 2007, the number of PET examinations performed with radiologist-owned scanners increased by 259%, while the number of PET examinations performed with non–radiologist-owned scanners increased by 737%. While this dramatic increase may be fueled, at least in part, by the economic incentive of self referral, it demonstrates the utility and rapid diffusion of this technology and suggests the need to establish standards of training and testing to assure the quality of medical services delivered.

Western Europe had 398 PET or PET/CT sites in 2008 (Fig 1), of which 22 (5.5%) were mobile, according to one survey (10). PET/CT systems accounted for 72% of all installed PET cameras, up from 57% in 2006. The average number of studies performed annually per scanner rose from 651 in 2002 to 1378 in 2008—an increase of 32.3% per year.

Commercial SPECT/CT systems have become increasingly available in the 11 years since the first commercial SPECT/CT units were produced. However, SPECT/CT systems have achieved less penetrance into the market than have PET/CT systems. Although the data are limited, estimates suggest that between one-third and one-half of new SPECT units are being sold as components of SPECT/CT systems (10) (Anthony N. Stevens, PhD, Medical Options, London, England, personal communication, January 2010). Prototype MR imaging/PET and MR imaging/SPECT systems have been developed, but no commercial systems incorporating MR imaging with PET or SPECT have been installed to date (14,15).

Global Trends in Hybrid Imaging Interpretation

The interpretation of PET/CT data requires knowledge of molecular biology and metabolism, as well as radiation chemistry and anatomic imaging. The importance of such dual expertise has grown along with the quality and quantity of CT data acquired in hybrid examinations (16). Although the majority of PET/CT examinations involve unenhanced low-attenuation CT, the use of full diagnostic CT examinations with contrast enhancement appears to be increasing around the world (2,5,9). Guidelines regarding the interpretation of PET/CT data are evolving. At present, PET/CT images are read mostly by nuclear medicine physicians, but growing numbers of radiologists are acquiring additional training in PET image interpretation or additional board certification in nuclear medicine (16). Radiologists' involvement in PET/CT interpretation varies by country, and there are countries (eg, Australia and Switzerland) where radiologists do not independently interpret PET or PET/CT images unless they are fully credentialed in nuclear medicine (16).

Overall, in Europe, Asia, and Australia, nuclear medicine physicians most often interpret the PET components of hybrid examinations, using unenhanced CT information for an anatomic frame of reference (2,9). Dual reporting of PET/CT (unenhanced CT) is also common, and performance of PET/CT interpretation solely by diagnostic radiologists is seen as well (2,9). Data on interpretation practices in the United States are limited, but it is clear that both nuclear medicine physicians and radiologists independently read PET/CT images, and dual reporting also occurs. Interpretation of PET/CT images by a diagnostic radiologist is more common in private practice than in academic centers (16).

The majority of PET and PET/CT studies worldwide continue to be performed in nuclear medicine or PET departments, because a license to handle open radioactive sources is required (16). In Australia, more than 90% of PET and PET/CT scanners are in nuclear medicine departments. In 2008, IMV identified and surveyed a total of 2000 PET and PET/CT sites in the United States; of the 1056 sites (53%) that responded, 43% were nuclear medicine departments, 32% were PET departments, 16% were radiology departments, and 6% were radiation oncology or medical oncology departments (6). Interestingly, while a substantial proportion of PET and PET/CT devices were in mobile facilities (285 in mobile facilities vs 1000 at fixed sites), 56% of fixed PET sites and 43% of fixed PET/CT sites were run by PET departments. In the United States, Europe, and Asia (particularly in India), the use of PET or PET/CT within radiology departments is increasing, especially in the private sector (16).

Global Trends in Accreditation and Training for Hybrid Imaging

To make optimal use of hybrid imaging in patient care, the health care team must be thoroughly trained in operating both the nuclear medicine and standard radiologic components of the hybrid-imaging suite. In addition, physicians must be trained to fully interpret both the anatomic and the molecular data acquired. This section reviews global trends in accreditation, training, and privileging in hybrid imaging.

Site Accreditation

Site accreditation is generally required for the use of PET or PET/CT. Typically, accreditation programs include requirements for the personnel, equipment, and processes involved in providing clinical services. For example, for nuclear medicine sites in the United States, standards must be met in the acquisition of both clinical and phantom images. Information on data collection, reporting, radiopharmaceutical procedures, and laboratory safety must be provided, and a program of continuous quality improvement must be in place. On the basis of our observations, while specifics vary from one country to another, the regulations are similar in the United States, the European Union, Asia, and Australia.

Technologist Training

In many countries, technologists who work with PET/CT are typically certified in either nuclear medicine or radiography but not both. In the United States, for example, the American Registry of Radiologic Technologists offers only separate primary certification programs in radiography and nuclear medicine technology. Although postprimary certification in CT is available, it is common to provide on-the-job training to teach a nuclear medicine technologist to operate the CT scanner.

The need for more consistent cross training of hybrid-imaging technologists could be addressed by changes in government regulations and training curricula. In Japan, for example, all technologists overseeing nuclear medicine sites must be certified by the Japan Association of Radiological Technologists, and for each PET or PET/CT unit, there must be at least one technologist who is experienced in nuclear medicine and trained in a designated educational program of the Japanese Society of Nuclear Medicine. In the United States, the Society of Nuclear Medicine Technologist Section and the American Society of Radiologic Technologists have jointly proposed a PET/CT curriculum (17), and similar initiatives are being pursued around the world. Standardized hybrid imaging curricula that include both didactic and practical experience components should be implemented and learning should be documented by close observation and proctored testing (16).

Physician Training

Currently, in North America, Europe, Asia, and Australia, it is common for nuclear medicine trainees to receive some training in radiology and vice versa. For example, in the United States, a 3rd year was recently added to nuclear medicine residencies to allow training for a minimum of 4 months in cross-sectional imaging, while radiology residents must undergo a minimum of 4 months of clinical rotations and 80 classroom hours of didactic instruction in nuclear medicine. In Australia, the possibility of adding a year to standard nuclear medicine training to develop expertise in cross-sectional imaging is being discussed.

A number of countries have established pathways for radiologists or internal medicine physicians to achieve subspecialty certification in nuclear medicine. For example, in the United States, radiology residents may complete a 1-year fellowship to become eligible for the American Board of Radiology subspecialty certificate in nuclear radiology, which encompasses nuclear imaging, the use of radiopharmaceuticals, and quality control of nuclear imaging instruments. Radiologists can also complete 1 year in a nuclear medicine residency program and become eligible for the American Board of Nuclear Medicine certificate. However, in many areas of the world, including the European Union, the United States, Australia, and Japan, for physicians whose primary specialty is nuclear medicine with an internal medicine background, there is no established route to subspecialization in diagnostic radiology other than the completion of a second full residency program.

Specialist qualifications required for formal interpretation of PET, SPECT, PET/CT, and SPECT/CT images vary widely. Most countries require specialized physician training and facility accreditation for PET reporting and reimbursement eligibility. In the United States, completion of a residency in either nuclear medicine or radiology includes training for the interpretation of PET and SPECT studies. However, individual institutions may set stricter requirements for interpreting PET/CT or SPECT/CT studies, and opinions differ as to what those requirements should be. Currently, radiology residents in the United States must have 4 months of training in nuclear medicine, but this includes all aspects of nuclear medicine. Thus, it is not clear how much PET or SPECT training they get. The nuclear medicine residency curriculum includes PET/CT training and dedicated CT training. In Australia, standard nuclear medicine training (3 years following internal medicine boards or 2 years following radiology boards) is necessary for any nuclear medicine reporting eligibility; furthermore, PET reporting requires additional training and interpretation experience that is not included in all nuclear medicine training programs.

The Need for More Extensive Cross Training in Nuclear Medicine and Radiology

Radiology and nuclear medicine are distinct imaging specialties with different areas of emphasis. Although training in radiology emphasizes anatomy and pathology, training in nuclear medicine emphasizes biochemistry and pathophysiology. As a survey of members of the EANM and the European Society of Radiology (ESR) (2) showed, specialists in both fields generally agree that more thorough cross training is needed to facilitate the optimal use of hybrid imaging.

In the training of radiologists, subjects especially in need of greater attention include radiotracer principles of molecular imaging, the biomathematics of tracer use (eg, compartment modeling and dosimetry), and imaging physics. Such subjects will become increasingly important as molecular imaging approaches based on radiotracers are integrated into individualized medicine. Conversely, nuclear medicine physicians need more extensive training in cross-sectional imaging. For example, 4 months—the minimum amount of time devoted to cross-sectional imaging in nuclear medicine residencies in the United States—may not be sufficient for gaining true competence in modern CT imaging, let alone the whole gamut of cross-sectional imaging studies (16).

Adequate cross training will be most easily accomplished by furnishing all programs with a common curriculum that allows trainees the flexibility to focus on the expected areas of practice and that is approved by appropriate radiology and nuclear medicine professional bodies and government, as per country-specific requirements. The issue is to provide sufficient time for developing a strong foundation of relevant CT and PET expertise under the supervision of skilled mentors. This issue is being addressed by most countries through dialogue between relevant organizations responsible for medical credentialing (18,19).

In the future, as the use of PET/CT, particularly with diagnostic contrast material–enhanced CT, increases and as MR imaging/PET becomes part of the imaging armamentarium, 2 or 3 years of traditional radiology training will likely be needed for nuclear medicine physicians (and vice versa for radiologists) to prepare them to use these hybrid imaging techniques optimally (16). To limit the duration of training, it may be necessary to omit certain subjects, such as the therapeutic applications of nuclear medicine, or highly specialized areas of diagnostic imaging, such as breast imaging or interventional radiology. In their position paper on multimodality imaging, the EANM and the ESR proposed 5–6-year training programs as a practical solution (18). Specifically, they suggested 3 years of training in the primary specialty, 2 subsequent years of training in the subspecialty with maintenance of primary specialty skills, and, for physicians with a nuclear medicine base, a final year devoted to radiology alone. In Japan, 5-year radiology training programs are now offered that render trainees eligible for board certification in nuclear medicine as well as radiology. Partly as a result of this, most board-certified radiologists in Japan are able to read nuclear medicine studies, and few physicians choose to be trained in nuclear medicine alone. In the United States, the Society of Nuclear Medicine, the American College of Radiology, and the Society of Computed Body Tomography and Magnetic Resonance jointly outlined possible PET and CT curricula for cross-training radiologists and nuclear medicine physicians (20). Although details of cross-training curricula must be negotiated between the nuclear medicine and radiology certifying boards in each country, the design and pursuit of global standards for cross-training would be desirable. In the long term, the most efficient option may be to develop a single curriculum, in which the anatomic/pathologic and biologic/pathophysiologic orientations of the two specialties would be integrated from the very beginning. Recently, training along this model was implemented in Sweden, after the National Board of Health and Welfare instituted the melding of nuclear medicine, radiology, and clinical physiology into a new specialty called "imaging and functional medicine." Residents in this specialty now undergo 3 years of core training that mixes the three component disciplines, followed by 2 years of subspecialty training in one of the three disciplines. Integrated training was favored by a large proportion of respondents to the ESR/EANM survey (2) and may become essential as clinical applications of hybrid imaging proliferate. Ideally, such training should include direct involvement in translational research, with training in research methodologies, ethics, and biostatistics. Such involvement is essential not only to advance research but also to enable clinicians to understand and apply new hybrid imaging probes and technologies in patient care.

The rapid pace of technologic change has made it enormously challenging to develop and maintain the competencies required for optimal PET/CT interpretation. The challenges are particularly great for radiologists and nuclear medicine practitioners whose training was completed before the clinical introduction of hybrid imaging. While some practicing physicians may choose to undergo a second residency to achieve expertise in both specialties, for many, such a commitment may not be feasible. Various short but intensive training programs have been created in different countries to enhance the hybrid imaging skills of practicing physicians. For example, a 4-week fellowship program in the interpretation of PET/CT offered in Zurich, Switzerland, has been attended in equal numbers by practicing radiologists and nuclear medicine specialists. The course includes supervised interpretation of about 300–400 PET/CT studies. In the United States, the American College of Radiology offers an intensive PET/CT course for diagnostic radiologists who have completed 6 months of training in nuclear medicine, have received or are eligible for certification by the American Board of Radiology, and have completed formal coursework in PET or PET/CT but have limited experience reading these studies in daily clinical practice. During an interactive session, participants interpret more than 150 PET/CT studies and receive immediate feedback on their performance. The Society of Nuclear Medicine has a similar program, offering courses in which the participants interpret 100 CT studies and receive immediate feedback. Although such programs cannot substitute for full subspecialty training, they may be effective for maintaining and improving the interpretive skills of practicing physicians. Results of recent studies (21,22) have shown that short but focused interactive training curricula can substantially improve readers' accuracy in interpreting specific types of studies (eg, virtual colonoscopy, MR imaging of the prostate).

As noted above, professional organizations such as the American College of Radiology, the Society of Nuclear Medicine, the EANM, and the ESR are involved in important efforts to establish practice guidelines for hybrid imaging that will ensure maintenance of competence and the safety and quality of patient care (19,20). The Japanese Society of Nuclear Medicine has focused its educational efforts on improving the understanding of PET, as nuclear medicine physicians without an educational background in radiology are rare in Japan. Efforts to promote cross training and maintenance of competence, quality, and safety are also underway in other Asian countries and in Australia. The guidelines developed should be consistent with established standards, and mechanisms should be encouraged that provide regular monitoring of the quality of hybrid imaging performance, including tools for identifying the need for remedial action. Furthermore, standards of training and testing to assure the quality of PET/CT must be extended to physicians who use this technology outside radiology and nuclear medicine.

The Benefits of Hybrid Imaging for Patient Care and Workflow

When PET was first introduced in the early 1990s, its high spatial resolution relative to that of other nuclear medicine modalities immediately set it apart and provided the spark for groundbreaking technical innovation. In 2000, after nearly 8 years of intense collaboration, Ronald Nutt, PhD, an electrical engineer at the manufacturer CTI (Knoxville, Tenn), and David W. Townsend, PhD, a medical physicist at the University of Pittsburgh (Pittsburgh, Pa), reported the creation and successful testing of the first PET/CT hybrid scanner (23). Rapidly, major manufacturers followed suit. PET/CT soon captured the imagination of the imaging community, and *Time* magazine named it the Medical Invention of the Year (in 2000). In 2010, there is no question that PET/CT has fulfilled its promise, having evolved into a mainstay of clinical imaging and replaced PEt alone in oncologic and infection imaging (24). The key reasons for this success are as follows:

1. The need for an anatomic frame of reference for PET with ^{18}F-FDG and other probes.

2. The relatively high spatial resolution (around 8 mm) of PET, which permits lymph nodes that appear normal anatomically to be classified as pathologic on the basis of their FDG uptake.

3. The ability of CT data to provide an attenuation map for PET, which makes PET/CT considerably faster than PEt alone and provides consistent image quality and semiquantitative uptake measures, which are needed in monitoring therapy.

4. The close temporal sampling of CT and PET, which provides near-contemporaneous fusion of structural and metabolic data.

These reasons for the success of hybrid PET/CT also apply to other hybrid imaging devices. The gamma camera and SPECT continue to be the workhorses of nuclear medicine in cardiac, bone, thyroid, and tumor imaging, and perhaps in response to the very rapid growth of PET/CT, the use of hybrid SPECT/CT for both clinical and research purposes is also growing. Clinically, SPECT/CT provides considerable added value in cardiac imaging procedures based on technetium 99m (^{99m}Tc) or thallium radiopharmaceuticals and in diagnostic oncology studies with common gamma-emitting radiopharmaceuticals, such as the ^{99m}Tc phosphonates (bone scanning) and indium 111 octreotide (for carcinoid and other endocrine tumors). When radiotracers are used for therapy, SPECT/CT is often used for posttreatment imaging (eg, after high-dose therapies with ^{131}I for thyroid cancer and ^{131}I metaiodobenzylguanidine for neuroendocrine tumors).

Although SPECT/CT hybrid systems are sold worldwide, a rigorous workflow and economic analysis may not support the use of SPECT/CT with a state-of-the-art multisection CT scanner in some clinical settings (25). Unlike PET/CT, where manufacturers are moving toward combining state-of-the-art PET and CT devices, SPECT/CT instrumentation is being marketed with a range of less expensive CT options to keep down total hybrid instrument costs. Still, SPECT/CT is likely to have an important research role while remaining useful for key clinical applications. The relatively slow image acquisition of SPECT compromises efficient CT scanner use, but with the recent development of very fast solid-state–based SPECT cameras, the integration of SPECT and CT may result in a better workflow. Most major universities throughout the world are purchasing state-of-the art hybrid SPECT/CT scanners. Internationally, high-end SPECT/CT continues to be largely in the domain of nuclear medicine groups.

MR imaging/PET devices for hybrid anatomic and metabolic imaging are also on the horizon, and methods of using MR imaging data to correct PET images for attenuation are being explored (26). MR imaging/PET is the only hybrid imaging modality for which experimental systems exist that allow simultaneous imaging (27). Prototype MR imaging/PET units have been developed by several manufacturers and are being tested at major research institutions. Technical problems that may limit the performance of PET in close proximity to magnetic fields are being overcome, but it is likely that fully integrated simultaneous MR imaging/PET scanners for clinical use are some years away.

The Future: Ensuring Progress through Collaboration

Around the world, regulatory requirements demand extensive clinical trials for new imaging and therapeutic agents. Therefore, while new molecular imaging probes offer enormous potential for advancing personalized medicine, introducing them into mainstream clinical practice will be a formidable logistic and financial challenge. Collaboration between institutions and disciplines can hasten progress. For example, in the United States, the Academy of Molecular Imaging, the American College of Radiology, and several other professional societies joined with the federal health insurance agency Medicare to organize the National Oncologic PET Registry. For patients with cancer who are Medicare beneficiaries, the costs of FDG PET examinations are now covered as long as the imaging data are entered into the registry. This practice is called coverage with evidence development. Since registration began in 2006, data have been collected in more than 100 000 patients, and studies based on these data have been used to help gain approval for routine reimbursement of FDG PET applications (28). In Australia, a prospective PET data collection project initiated in 2003 collected data in more than 30 000 consecutive patients referred for PET over a 2-year period, and analyses of the data were used to expand the number of PET indications that qualify for reimbursement (29). A similar program has been conducted in Canada (30).

Interdisciplinary collaboration within institutions will also be essential to fully exploit the potential of molecular imaging and theranostics. Not only must nuclear medicine physicians and radiologists collaborate with each other, with radiation chemists, and with medical physicists, they must be integrally involved in patient care. This will help ensure that available hybrid imaging techniques are used appropriately and that new and innovative applications continue to evolve.

References

1. Dunnick NR. Opinion. Report of the 2002 Intersociety Commission meeting: Radiology 2002—today's research is tomorrow's practice. AJR Am J Roentgenol 2003;180(4):925–928.
2. Cuocolo A, Breatnach E. Multimodality imaging in Europe: a survey by the European Association of Nuclear Medicine (EANM) and the European Society of Radiology (ESR). Eur J Nucl Med Mol Imaging 2010; 37(1):163–167.
3. Bourgeat P, Chételat G, Villemagne VL, et al; AIBL Research Group. Beta-amyloid burden in the temporal neocortex is related to hippocampal atrophy in elderly subjects without dementia. Neurology 2010;74(2):121–127.
4. Rowe CC, Ackerman U, Browne W, et al. Imaging of amyloid beta in Alzheimer's disease with 18F-BAY94-9172, a novel PET tracer: proof of mechanism. Lancet Neurol 2008;7(2):129–135.
5. Report of IAEA Asia Pacific PET meeting. Vietnam, November 2009.
6. IMV Medical Information Division 2008 PET Market Summary Report. http://www.imvinfo.com/index.aspx?sec=pet&sub=dis&itemid=200076. Accessed February 2, 2010.
7. US Census Bureau. 2009 Statistical abstract. http://www.census.gov/compendia/statab/2009/2009edition.html. Accessed March 13, 2010.
8. The World Bank. World development indicators. http://data.worldbank.org/indicator/SP.POP.TOTL. Accessed March 13, 2010.
9. Nogami M, Sugimura K. Survey of multimodality imaging in Asia, November, 2009. Presented at: International radiology trends meeting on hybrid imaging, consensus discussion. Annual Meeting of the Radiological Society of North America; December 1, 2009; Chicago, Ill.
10. Stevens AN. Development of PET in Western Europe. Proceedings of the Annual Congress of the European Association of Nuclear Medicine, PW138, 2009.
11. Cherry SR. Multimodality imaging: beyond PET/CT and SPECT/CT. Semin Nucl Med 2009;39(5):348–353.
12. Mawlawi O, Townsend DW. Multimodality imaging: an update on PET/CT technology. Eur J Nucl Med Mol Imaging 2009;36(Suppl 1): S15–S29.
13. Agarwal R, Levin DC, Parker L, Rao VM. Trends in PET scanner ownership and leasing by nonradiologist physicians. J Am Coll Radiol 2010;7(3):187–191.
14. Hicks RJ, Lau EW. PET/MRI: a different spin from under the rim. Eur J Nucl Med Mol Imaging 2009;36(Suppl 1):S10–S14.
15. von Schulthess GK, Schlemmer HP. A look ahead: PET/MR versus PET/CT. Eur J Nucl Med Mol Imaging 2009;36(Suppl 1):S3–S9.
16. International radiology trends meeting on hybrid imaging, consensus discussion at Annual Meeting of the Radiological Society of North America. December 1, 2009; Chicago, Ill.
17. American Society of Radiologic Technologists and Society of Nuclear Medicine Technologist Section. Positron Emission Tomography (PET)-Computed Tomography (CT) Curriculum (2004). http://interactive.snm.org/index.cfm?PageID=2760. Accessed February 11, 2010.
18. Bischof Delaloye A, Carrió I, Cuocolo A, et al. White paper of the European Association of

Nuclear Medicine (EANM) and the European Society of Radiology (ESR) on multimodality imaging. Eur J Nucl Med Mol Imaging 2007;34(8):1147–1151.

19. Gourtsoyiannis N, McCall I, Reiser M, et al. White paper of the European Society of Radiology (ESR) and the European Association of Nuclear Medicine (EANM) on multimodality imaging. Eur Radiol 2007;17(8):1926–1930.

20. Coleman RE, Delbeke D, Guiberteau MJ, et al; Joint Working Group of the American College of Radiology; Society of Nuclear Medicine; Society of Computed Body Tomography and Magnetic Resonance. Concurrent PET/CT with an integrated imaging system: intersociety dialogue from the Joint Working Group of the American College of Radiology, the Society of Nuclear Medicine, and the Society of Computed Body Tomography and Magnetic Resonance [Review. Erratum in: J Am Coll Radiol. 2005 Sep;2] [9]. J Am Coll Radiol 2005;2(7):568–584.

21. Akin O, Riedl CC, Ishill NM, Moskowitz CS, Zhang J, Hricak H. Interactive dedicated training curriculum improves accuracy in the interpretation of MR imaging of prostate cancer. Eur Radiol 2010;20(4):995–1002.

22. Dachman AH, Kelly KB, Zintsmaster MP, et al. Formative evaluation of standardized training for CT colonographic image interpretation by novice readers. Radiology 2008;249(1):167–177.

23. Beyer T, Townsend DW, Brun T, et al. A combined PET/CT scanner for clinical oncology. J Nucl Med 2000;41(8):1369–1379.

24. Townsend DW. Dual-modality imaging: combining anatomy and function. J Nucl Med 2008;49(6):938–955.

25. von Schulthess GK, Burger C. Integrating imaging modalities: what makes sense from a workflow perspective? Eur J Nucl Med Mol Imaging 2010;37(5):980–990.

26. Hofmann M, Pichler B, Schölkopf B, Beyer T. Towards quantitative PET/MRI: a review of MR-based attenuation correction techniques. Eur J Nucl Med Mol Imaging 2009;36(Suppl 1):S93–S104.

27. Wehrl HF, Judenhofer MS, Wiehr S, Pichler BJ. Pre-clinical PET/MR: technological advances and new perspectives in biomedical research. Eur J Nucl Med Mol Imaging 2009;36(Suppl 1):S56–S68.

28. The National Oncologic PET Registry Web site. http://www.cancerpetregistry.org/what.htm. Accessed March 15, 2010.

29. Scott AM, Gunawardana DH, Kelley B, et al. PET changes management and improves prognostic stratification in patients with recurrent colorectal cancer: results of a multicenter prospective study. J Nucl Med 2008;49(9):1451–1457.

30. Evans WK, Laupacis A, Gulenchyn KY, Levin L, Levine M. Evidence-based approach to the introduction of positron emission tomography in Ontario, Canada. J Clin Oncol 2009;27(33):5607–5613.