Guest Editorial

MULTIMODALITY IMAGING has always been a part of nuclear medicine. Given the physiological nature of nuclear imaging, there has regularly been a need for anatomical correlates. Physicians have and will continue to use all available modalities to improve or focus their diagnoses. When one scan is not diagnostically decisive, a physician may turn to another modality for confirmation or additional information. Nuclear medicine physicians have used computed tomography (CT) scans to localize anatomically a tumor visualized on positron emission tomography (PET) or single photon emission computed tomography (SPECT). Referring cardiologists have used angiograms in conjunction with a myocardial perfusion study to determine the best treatment for coronary artery disease.

In the past, images from different modalities were acquired at different times, in different locations. Thus, there was no inherent alignment between them, and they had to be aligned, or registered, implicitly in the mind of the radiologist, nuclear medicine physician, or even the referring physician so that the information in each could be combined or compared. The primary example of this is the physician reading a tumor scan with the CT film of the same patient on a light box. Determining which point in the PET or SPECT image matches a certain point in the CT image requires a great amount of anatomical knowledge along with three-dimensional orientation and mental interpolation abilities.

In the early eighties, the advent of faster computers and better communication between computers helped lead to software methods for explicit registration of two or more scans. Researchers were able to attach external markers to the head that could be visualized in both SPECT and CT or magnetic resonance imaging (MRI). These points could be identified in the resulting images and matched up by using computer software. Once the points were aligned, the whole image sets were also aligned, so that one pixel on the nuclear medicine image matched exactly the same pixel on the CT image. The explicit alignment of the images improved confidence about anatomic localization of a defect in the nuclear medicine images.

In the late eighties, a more automatic technique was proposed to explicitly align head images. This computer algorithm matched up head surface boundaries obtained from a CT image to those obtained from a PET image. Both the surface boundary detection and the matching of the boundaries were performed automatically. The researchers used this algorithm with surgical planning techniques to improve localization of brain tumors and to minimize surgical trauma. The success of the technique and the impressive utility of the results helped lead to a surge of interest in medical image registration.

Early nineties work was still primarily focused on registration of brain images. Methods that used the images themselves, rather than surface boundaries, were introduced and were shown to be very robust for many types of images. Because these methods did not require preprocessing of the images for boundary detection, they could frequently be made completely automatic. An immediate application for these methods was found in fusing PET and MR images of the brain for discrimination of tumor recurrence from necrosis in brain cancer post radiation therapy. In such cases, an exact match of the images is necessary to identify and to localize small areas of recurrence.

Through the nineties, registration of body images was performed interactively, with users rotating and translating one image to match another or picking out common points between the two images so that these reference points could be matched. This type of interactive alignment is very difficult and very time-consuming. More importantly, body images, unlike brain images, cannot generally be aligned by using just a rigid transformation. The body is not rigid itself and may be positioned very differently in one scanner compared with another. For example, a pillow placed under the lumbar spine in one scanner will certainly bend the torso image from that acquisition. The bending cannot be "removed" from the image just by rotating and translating it. An "unbending" transformation must be applied somehow. As it turns out, brain researchers were also interested in this type of warping transformation to combine or compare brain scans from different patients. In this type of intersubject alignment, completely different morphology of the gyri and sulci also makes rigid transformations insufficient. Therefore, most of the nonlinear, warping registration algorithms were originally developed for intersubject brain alignment. In many cases, researchers were attempting to define normal anatomy or normal brain function by combining data from many subjects. Groups of abnormal patients could then be compared with this normal benchmark.

Toward this end, they developed various elegant and sophisticated algorithms to warp one image into another. However, these methods were developed primarily to warp images from the same modality and presumed that information in the images was similar. For example, most of these algorithms were designed to match MR brain images. While anatomy may be different from one person to another, at least the MR images from both people will show brain anatomy. This is not the case when we discuss warping of anatomical data to physiological data of the same person. The information in the images themselves is very different. Thus, these algorithms developed for inter-

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subject intramodal brain warping were not easily translatable to intrasubject multimodal body warping.

In the late nineties, the spreading of PET centers and the utility of [^{18}F]-fluorodeoxyglucose (FDG)-PET for detecting cancer started driving the need for fusion of anatomical images with the nuclear medicine images in the body. CT is generally the anatomical image of choice for localizing cancer in the torso, and nuclear medicine physicians were starting to request and even demand a correlative CT image when reading the PET image. Because software solutions were not available, university and company research started focusing on a hardware solution. Nuclear medicine companies began designing dual-modality PET-CT and SPECT-CT machines so that the CT and nuclear images could be acquired sequentially. Having the images acquired at nearly the same time at the same location could help ensure that the body was in the same position in both scans and obviate the need for complex warping algorithms. Hardware, then, is the currently dominant development area in registration technology for nuclear medicine. These new scanners can combine diagnostic quality CT scans with FDG images of the same patient. With this approach, there are no network, communication, or file format translation difficulties trying to get data from two different types of machines, and the images are already (nearly) aligned. However, there are still some misalignments in the images caused by patient motion, including breathing, that need to be addressed by software solutions. Nevertheless, these scanners are providing exquisite images and new opportunities and challenges.

Aside from the remaining non-linear registration challenge, numerous questions remain regarding how the multimodal images can be most effectively used after they are aligned. Currently, there is no standard display technique for fused images; even this seemingly simple issue has not been adequately addressed. Researchers in PET and SPECT reconstruction techniques can use the high resolution CT images as a basis for creating more accurate attenuation maps and for improving attenuation, scatter, and detector response correction algorithms. Use of the fused images for radiation or surgical therapy planning has received some attention recently, but will require more research to prove efficacy. Non-oncological applications, such as cardiology, may also benefit from dual modality scanners, as high resolution anatomical cardiac and coronary structural information is provided with important physiological data, all in registration. Finally, fusion of multimodal data needs to move beyond mere display to true integration of the data. Full use of the available data requires the combination of quantitative anatomic and physiologic information and its demonstration of prognostic, diagnostic, and therapeutic utility.

In this issue, we have attempted to assemble a collection of articles from leaders in the field of multimodality imaging in nuclear medicine. Dr. Brian Hutton and his colleagues address software approaches for fusing nuclear medicine images with other modalities. Dr. Rik Stokking and his co-authors discuss the topic of how best to display fused images. Drs. David Townsend, Thomas Beyer, and Todd M. Blodgett describe hardware solutions for registration, most importantly, the design of PET-CT machines. Dr. Paul Kinahan and colleagues lend their expertise to the topic of the acquisition, processing, and use of CT images for attenuation correction in PET and SPECT. Drs. Christian Cohade and Richard Wahl discuss practical aspects of PET-CT imaging and its applications. Dr. Zohar Keidar and his colleagues present technical and clinical elements of SPECT-CT imaging. Finally, Dr. Arnold Paulino et al describe the current use of fused images in radiotherapy planning. Overall, the articles address the current state of the art, both technologically and clinically, and provide an overview of the science behind fusion as well as its utility in the clinic. In the future, we hope to see truly integrated, more accurate, knowledge-driven diagnoses as this very active field develops.

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