ABSOLUTE CALIBRATION OF IN VIVO MEASUREMENT SYSTEMS USING MAGNETIC RESONANCE IMAGING AND MONTE CARLO COMPUTATIONS

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ABSTRACT

Lawrence Livermore National Laboratory (LLNL) is currently investigating a new method for obtaining absolute calibration factors for radiation measurement systems used to measure internally deposited radionuclides in vivo. This method uses magnetic resonance imaging (MRI) to determine the anatomical makeup of an individual. A new MRI technique is also employed that is capable of resolving the fat and water content of the human tissue. This anatomical and biochemical information is used to model a mathematical phantom. Monte Carlo methods are then used to simulate the transport of radiation throughout the phantom. By modeling the detection equipment of the in vivo measurement system into the code, calibration factors are generated that are specific to the individual. Furthermore, this method eliminates the need for surrogate human structures in the calibration process. A demonstration of the proposed method is being performed using a fat/water matrix.

INTRODUCTION

Current calibration methods for in vivo systems recognize the strong geometric dependence of the process. The validity of the actual counting results is directly related to the similarity of the distribution of radioactivity and absorbing medium used in the calibration procedure to that of the individual being measured. For this reason, surrogate human structures, or phantoms, are used to represent the human body during calibration. A phantom is loaded with a known quantity of radioactivity and then measured by the counting system in a manner representative of human-subject measurements. By this means, appropriate calibration factors can be determined for the system.

Much emphasis has been placed upon the development of realistic phantoms. The number of organs included in more recent phantom models has increased, as has their detail with regard to size and shape. More attention has also been given to the use of tissue-equivalent materials in constructing phantoms. Despite their increasing complexity, the fundamental problem remains that a phantom represents the "average" characteristics of the human body. Significant corrections must still be made to obtain calibration factors that are applicable to a given individual. Hence, a calibration method is needed that is more sensitive to variability between individuals with regard to anatomical and biochemical differences. A new calibration method being developed at LLNL achieves this objective through the use of MRI.[1]

METHOD COMPONENTS

MRI techniques induce a strong, uniform magnetic field throughout the human body, reorienting the spin axis of atoms with magnetic properties. Radiofrequency pulses are then transmitted through the field, perturbing these aligned atoms. Subsequent energy dissipations by the excited nuclei are detected and used to identify the type of tissue being imaged. An anatomical layout of the individual is then determined based on the characteristic resonating patterns of different tissue types.

An advantage of MRI over conventional x-ray imaging techniques (e.g., computed tomography) is that it does not use ionizing radiation and is thus considered to be biologically safe. Additionally, MRI offers biochemical information not obtainable by other imaging modalities. A new MRI method developed at Stanford University improves upon the Dixon technique for obtaining fat and water images.[2] This method uses a magnetic resonance image that is a measure of the inhomogeneities in the induced magnetic field, B_0. This information is used to correct the fat, water, and fat-plus-water data to yield true fat/water images.

The usefulness of this detailed biological data to calibration procedures is realized by using Monte Carlo methods. The MRI data is used to define a radiation transport medium within a Monte Carlo code. Various tissues or organs of the body are selected as containing sources of radioactive material. Radiation detectors and their location relative to the radioactive material are then modeled into the code. The code then simulates the transport of radiation throughout the medium, repeatedly sampling its library of interaction properties for the MRI-determined biological data. Tallies are recorded for each radiation penetrating the detectors. The code thus simulates the calibration of the in vivo measurement system for the particular subject; i.e., performs an individual-specific calibration.

The development of this method is being performed using the Monte Carlo code MCNP4.[3] The input file format for this code lends itself well to this application, allowing for the definition of a cube representing each voxel of MRI information. The code is available on numerous operating environments, particularly the VAX and PC machines, and has been validated through years of countless users producing credible results. Quality assurance studies are planned by comparing results obtained using MCNP4 with those produced by other codes, namely MORSE and EGS4.[4]

DEMONSTRATION OF METHOD

The calibration method was demonstrated using a fat/water matrix. The sample was composed of a beef rib bone, sponge, and deionized water enclosed in a polypropylene container (see Fig. 1). A small plastic vial containing natural uranium (1.38 kBq U^{238}) in solution was also present. The enhanced Dixon images were obtained using a General Electric 1.5-T SIGNA unit. Coronal plane images were made for a 3-mm slice, 24-cm field of view. Figure 2 displays the fat, water, and B_0 images generated.

The Monte Carlo code calculations proceed as follows. The integer data for each magnetic resonance image are reformatted into an acceptable input file for the MCNP4 code. Material specifications are made for each voxel based on a decision tree comparing the ratios of the integer values in the fat, water, and fat-plus-water images. Detector systems must also be modeled into the code in an identical manner to the actual counting system used. Tallies record the energy spectrum of photons entering the detector's sensitive volume.

Calculation of calibration factors requires an additional Monte Carlo operation. A single point source, in this case the sample vial of natural uranium described above, is counted by the detector system in the absence of any additional attenuating medium. The layout is also modeled into MCNP4 and processed by the code. Resulting tallies, when ratioed by the activity of the source, measure the intrinsic efficiency of the detection system. This factor must be included in the final determination of calibration factors for the in vivo measurement system.

DISCUSSION

The method's demonstration has pointed to three areas that require further review. First, the MRI data for multiple slices may exceed the memory capacity of the computer running MCNP4. Each slice is composed of 256 × 256, 2-byte integer data. The method requires three Dixon images per slice; i.e., fat, water, and fat-plus-water. Assuming a conservative 1-cm slice thickness, the memory requirements for the MRI data alone for the adult lung region could approach 10 mega bytes. Hence,

the computer's memory may be taxed by the MCNP4 input file considering the additional geometry and material specifications required. Towards this end, we are researching optimization of the computer hardware; i.e., extending computer memory. Another solution is the addition of adjacent voxels of similar tissue type. Convolution techniques such as 5-point and 9-point smoothing can be used to efficiently encode the input files. However, the reduced sensitivity from joining like voxels must also be investigated.

A second issue to be considered is the defining of organ boundaries within the MCNP4 code for assigning source distributions. A likely solution will be the use of an algorithm using the Laplacian technique for automatic edge detection. This also raises the third topic of concern, which is defining the source location within the tissue and organs of the individual. Uniform distribution within the lung tissue is the principal mode of calibration and will be the standard in developing this method. However, the input file to MCNP4 can easily be revised to accommodate whatever source distribution is desired.

This new method will be verified using a specially designed phantom. This phantom will be constructed of a plastic that can be imaged by MRI techniques. Various compartments within the phantom will be available for redistributing radioactive sources and absorbing media while providing a method for consistently reproducing measurement results. Additionally, a MRI data base of human volunteers, selected on the basis of varied body sizes and shapes, is being compiled. This data base will be used to assess the validity of a correlation between biometric data for an individual (e.g., height, weight, and chest-wall thickness) and the calibration method described here.

ACKNOWLEDGMENT

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Figure 1. The fat/water matrix (sagittal plane) is composed of a beef rib bone, two sponges, and a plastic vial containing 1.38 kBq U^{238} in solution. The container is composed of polypropylene and filled with deionized water.
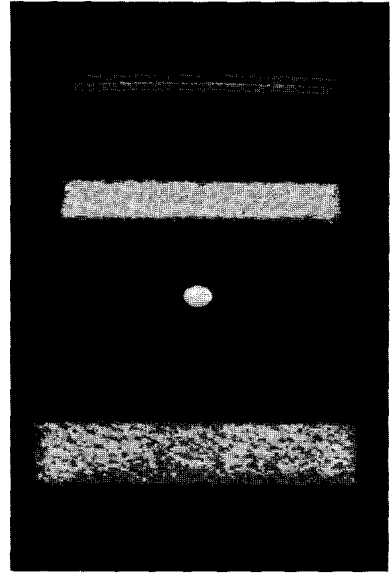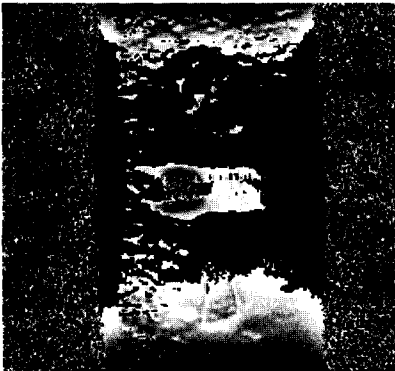
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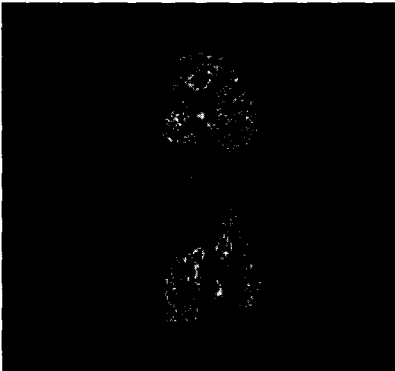
(b)

(c)

Figure 2. Enhanced Dixon images (coronal plane) of the fat/water matrix. (a) fat, (b) water, (c) B_0.