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Absolute Calibration of *In Vivo* Measurement Systems

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Absolute Calibration of *In Vivo* Measurement Systems

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*. Absolute calibration of *in vivo* measurement systems will eliminate the need to generate a series of human surrogate structures (i.e., phantoms) for calibrating *in vivo* measurement systems. The absolute calibration of *in vivo* measurement systems utilizes magnetic resonance imaging (MRI) to define physiological structure, size, and composition. The MRI image provides a digitized representation of the physiological structure, which allows for any mathematical distribution of radionuclides within the body. Using Monte Carlo transport codes, the emission spectrum from the body is predicted. The *in vivo* measurement equipment is calibrated using the Monte Carlo code and adjusting for the intrinsic properties of the detection system. The calibration factors are verified using measurements of existing phantoms and previously obtained measurements of human volunteers.

Introduction

Medical imaging of the human body has been greatly enhanced with the development of MRI. The three-dimensional information obtained using MRI provides an exact measure of physical size, shape, and composition of human organs and tissues. These images are in digital format, which allows computer enhancement and interpretation. MRI is a relatively new medical imaging modality, and its use has significantly increased over the past few years in the United States. An advantage of MRI over other similar imaging modalities (e.g., computerized tomography [CT]) is that it provides increased detail of physiological structure with no known physical risk to the patient.

With the increased use of MRI comes a data base of information regarding physiological structure and composition. This data base of digitized images is an ideal data pool for development of a mathematical set of exacting human surrogate structures (i.e., phantoms). This set of phantoms could then be used to define a "standard" phantom for use by the nuclear industry to generate *in vivo* measurement calibration factors for internally deposited radionuclides.

The digitized images obtained from MRI are used mathematically to define source locations and distributions according to the physiology and biokinetics of the calibration radionuclide, thus providing a digitized geometry to be used by a continuous-energy Monte Carlo transport code. The Monte Carlo code would apply corrections for attenuation through various physiological structures and tissue compositions as determined from the MRI image data. This results in a photon emission spectrum out of the body that would be available for detection by *in vivo* measurement systems.

When a continuous-energy Monte Carlo code is used in conjunction with response characteristics of the detector system, the absolute efficiency for the detector system is determined for the MRI image (i.e., standard phantoms). The continuous-energy code allows for correction of the photon emission spectrum for photopeak broadening (i.e., resolution) and provides the absolute efficiency for any region of interest

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chosen within the photopeak area. Daughter radionuclides and other interfering radionuclides can also be incorporated into the source code, thereby providing an absolute calibration for any combined spectrum of radionuclides.

Verification of the absolute calibration technique for *in vivo* measurement systems is necessary before routine use at nuclear facilities. Currently, there are several human surrogate structures (i.e., constructed phantoms) and human volunteer radionuclide studies that can be used for verification. MRI scans are planned using the thoracic phantom developed by LLNL and the U. S. transuranium registry case 102 bone phantom.

Using these scans and known information regarding the radionuclide distribution within the various organs of these phantoms, a source geometry will be established for use by the Monte Carlo code in determining absolute calibration values. These absolute calibration values will be compared to measured calibration values for these phantoms.

In the 1980s, *in vivo* measurement studies using human volunteers who inhaled ^{92m}Nb were compared to each other. MRI scans were performed to define physiological and compositional structures of the volunteers. As part of the verification process for the absolute calibration technique, the intercomparison data will be reevaluated relative to computed calibration values.

In summary, the absolute calibration technique currently under investigation eliminates the need to physically construct human surrogates and can be used to define a standardized phantom for routine use by *in vivo* measurement systems. For nonroutine use (i.e., a measured intake of radioactive material), an MRI scan obtained for the individual containing the radioactive material could be used to determine exact calibration parameters according to the individual's physiological structure and composition.

Magnetic Resonance Imaging

Concept

Nuclear magnetic resonance (NMR), the predecessor to MRI, is a powerful tool used to identify the structure of chemicals, as well as interactions between nuclei of materials and biological systems. Although conventional applications of NMR do not allow the location of magnetically stimulated nuclei to be determined, recent developments have made imaging possible by spatially encoding the emitted signal from specific nuclei in the sample.

MRI, as this process became known, uses the signals emitted from resonating nuclei (most commonly hydrogen) in the body to create an image of all or part of the body. Spatial information is obtained by applying gradient (or varying) magnetic fields over a stronger, uniform magnetic field. The gradient fields cause the nuclei at each position in the body to resonate at different frequencies. The signal receiver is tuned to accept a specific frequency; thus, when signals are received, they are a direct indication of the position from which they were generated. Signal relaxation times depend on the molecular environment of the tissue and, hence, the type of tissue from which the signal was generated.

The mid-twentieth century brought about the first successful NMR experiments in solids and liquids. Rapidly improved methods were developed, and soon the idea of controlling the nonuniformity of magnetic fields to identify the spatial coordinates of nuclei spawned the generation of three-dimensional images. Soon the medical community began to learn of the usefulness of this technique, and in 1973, the first MRI images were published.[1]

Current State-of-the-Art

Today, MRI surpasses other imaging techniques. MRI is more versatile and retains all of the positive aspects of other imagining techniques without retaining the known disadvantages. The spatial resolution is improving daily and is comparable to, if not surpassing, CT imaging. The contrast of MRI exceeds 500 percent in soft tissue, thus providing excellent anatomical detail.[2] This anatomical detail is

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the predominate feature of MRI that is used to establish a realistic phantom for Monte Carlo computations of photon transmissions in the body.

Development of a Mathematical Phantom

The digitized, three-dimensional spatial representation of the human subject is the basis for constructing a mathematical phantom to be used by a Monte Carlo code. Standard imaging techniques will (1) be used to define organ/tissue structure and interfaces in three-dimensional space, and (2) supply exact tissue density data for determining photon capture, scatter, and leakage probabilities.

The digitized information obtained from MRI, known as voxels, provide exact data on the material characteristics encountered by the histories of photons as they are guided by Monte Carlo probability. The MRI voxels transmitted from medical procedure tapes also provide shell images that can assist in visualization and optimization of the calibration process. The voxel information and images are retained and stored on a VAX 3200 computer system.

Photon Emission Computations

Concepts

Monte Carlo techniques have been extensively used to describe radiation transport in matter. Most Monte Carlo techniques use the macroscopic principles and formulations to establish a probability distribution of interaction for a large number of photons. This distribution provides boundary conditions for interactions. The interaction of a single photon within this probability distribution is determined using a random number generator, which is analogous to throwing dice. Interactions are defined according to the type (i.e., scatter, absorption, or leakage). Histories of each photon are maintained, and as more histories are obtained, photon distributions become better known. The quantities of interest (e.g., photon flux and energy flux) are tallied along with estimates of statistical precision for the results.

Current State-of-the-Art

Monte Carlo codes are used to calibrate radiation detection systems. Some facilities use Monte Carlo techniques exclusively to calibrate measurement systems and use the National Institute of Standards and Technology (NIST) traceable sources to check the calibration. With improved microprocessors, the computational codes are faster and continue to be programmed onto smaller and smaller computer systems. The operation of Monte Carlo codes on a VAX 3200 workstation is an example of new technology interfacing with improved programming concepts. Libraries of nuclear data reactions and branching fractions for radioactive daughters have been developed, thereby enhancing repetitive operations and allowing computations of photon fluxes for mixtures of radionuclides.

Interfacing with a Mathematical Phantom

Monte Carlo code requires source specification. The degree of accuracy in the final result is highly dependent on the source specification, geometry, and reaction probabilities as photons traverse tissue. Voxels of data are used to describe the three-dimensional location and composition of sources and attenuating tissues/organ. As photons traverse a voxel, its reaction probability is controlled by the physical attenuation parameters.

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Determination of Intrinsic Detector Parameters

Detector response functions that are calculated from first principles using Monte Carlo techniques do not account for inefficiencies in the detector system (i.e., light collection efficiency of the NaI detector); however, many codes allow input of a correction factor to account for inefficiencies. Alternatively, the response function of the detector can be measured and folded into the Monte–Carlo-computed incident photon flux spectrum.[3–5] Each of the two techniques has advantages and disadvantages. For instance, folding the measured response function into the computed incident photon spectrum does not correct for scatter from nearby structures. Both of these techniques are being investigated to evaluate the optimum method for generating efficiency factors for *in vivo* measurement systems.

LLNL has HpGe, Phoswich, and large crystal NaI detection systems. The incident photon spectrum computed using Monte Carlo codes is combined with measured responses and/or computed detector response functions to generate individual detector efficiency factors. The response function is then used to assess individual detector efficiency factors. The computed efficiency factors will be compared to measured efficiency factors for the various types of calibration phantoms used at LLNL (see the following section). From these comparisons, the optimum method for calibration of *in vivo* measurement systems can be selected.

Verification of Absolute Calibration Technique

Verification of the absolute calibration technique has been considered. Currently several types of *in vivo* measurement phantoms exist. These phantoms could be biomedically imaged/digitized and used as mathematical source terms for the Monte Carlo photon emission computations. The efficiency will be determined for the computed photon emissions spectrum and compared to the measured spectrum of each phantom using the various detector systems available at LLNL.

Further verification may be possible using data collected for human volunteers who inhaled ^{92m}Nb. MRI scans of these volunteers were obtained prior to inhalation of ^{92m}Nb. These images could be used to establish each individual's mathematical source term for the Monte Carlo computations. Efficiency factors could then be computed for the LLNL detectors. Because LLNL participated in intercomparison measurements of these volunteers, the measured efficiency factors could then be compared to the computed efficiency factors. This verification would provid strong evidence for the validity of the absolute calibration technique.

Discussion and Conclusions

Biomedical imaging techniques are capable of defining detailed structures for the *in vivo* measurements. A magnetic resonance image could be produced for each *in vivo* measurement subject and an exact phantom representation produced for that individual. Alternatively, an "average" phantom could be established for routine *in vivo* measurements (i.e., measurements that demonstrate no detectable activity), thus eliminating the need to generate an MRI scan of each individual. An average phantom will be obtained by evaluating the data base of MRI scans currently available.

Monte Carlo techniques have previously been used to compute absolute measurement efficiencies for *in vivo* measurement systems.[6–8] However, these previous computations used theoretical phantoms that were physiologically inadequate (e.g., both lungs were of equal size). Biomedical imaging will provide an exact replication of the individual physiology. Organ sizes, shapes, and tissue compositions (i.e., fat, muscle,

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and bone) will be realistic for the individual being measured. Assumptions for establishing absolute calibration factors will be limited to considerations of radionuclide distribution between and within organs/tissues.

NIST has proposed to standardize *in vivo* measurements using a selected number of phantoms. The absolute calibration technique will extend beyond the concept of constructing singular phantoms to simulate actual human structure. The absolute calibration will be more exacting by using the measured human structure. In fact, this technique could serve as the NIST standard.

The final development stage for this research project will be to apply the absolute calibration technique to *in vivo* measurement system computer operations. This would allow absolute calibrations using simple computing equipment such as personal computers. This final development stage will provide users with a simple environment for the calibration of site-specific *in vivo* measurement equipment. An Autocad computer program can also be used to visualize the conceptual phantom and radionuclide source distributions relative to detector placement.

Absolute calibration of *in vivo* measurement systems is the final end point for developing photon transmission phantoms, which can be "average" phantoms or individually specific phantoms with exacting detail. Construction of phantoms will be computational rather than physical, making phantom construction economically feasible. Radioactive source distributions can be placed into any organ/tissue or any group of organs. Source terms can be treated either as macro distributions or micro distributions. The absolute calibration technique allows for calibration of different types and configurations of detectors, including future designs of *in vivo* measurement systems.

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