Simulation System for Radiology Education Integration of Physical and Virtual Realities: Overview and Software Considerations

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Abstract. The aim of the proposed system is to give the students a flexible, realistic, and interactive learning environment to study the physical limit of different postures and various imaging procedures. The suggested system will also familiarize the students with various imaging modalities, the anatomical structures that are observable under different X-ray tube settings and the quality of the resulting image. Current teaching practice for radiological sciences student asks students to simulate the imaging procedure in role plays – a student to be a patient and the other as the radiologist. Other ways include the use of physical phantom with bone and soft tissue equivalent material but still the use of X-ray have to be used with all the requirement of such examination to be in place, e.g., room shielding, lead apron, and other radiation protection procedure. The proposed system has several physical components and virtual components. Students manipulate the mannequin into the model of the imaging modality and in a posture suitable for the purpose of the imaging study. The virtual components of our simulation system include a posture interface, a computational phantom generator, and a physics simulator. The synthetic image will be produced and conform to the Digital Imaging and Communications in Medicine standard so that it can be stored, retrieved, and displayed in a standard picture archiving and communication system that hospitals use.

Introduction

Simulation nowadays covers a wide spectrum in meaning and in application depending on the field that it is applied. Among all fields of sciences, the flight simulator for training pilots is perhaps the best-known simulation system. It familiarizes the trainee with the airplane cockpit and different situations that may arise. Before the trainee pilot takes off in a real airplane, he has already accumulated valuable experience of difficult situations that may not arise even throughout his career as a qualified pilot, and without risk to himself and passengers. The idea had been taken-up well by educators in many disciplines and extended to medical sciences in which the well-being of patients is of paramount importance. Simulations alleviate the needs to practice on real patients to sharpen the skill of the clinician.[1] In fact, simulation was said to be the 'ethical imperative' in some areas of medical education.[2,3] Furthermore, simulations were shown to offer improved learning and better knowledge acquisition and retention when compared to conventional lectures[4] because skills were learned and reinforced in an iterative manner.[5] They are and will be an important aspect in all medical training.[6-9] Within medical sciences and related radiology training, simulation systems have been developed for, for examples, surgery[6,8,10] cardiac examination,[11] catheter administration,[12] ultrasound examination[13,14] to name but a few.

In addition to the balance between patient safety and clinical skills, radiological education also poses a further risk of radiation exposure to the students if practiced on real equipment that utilizes ionizing radiation such as X-ray and computed tomography (CT).

Simulations remove this concern completely from the learning process. In the education and training of radiographers, radiologists, and other related areas of radiology, the trainees study various X-ray-based imaging systems and the procedures that imaging examinations are conducted. The training requires their understanding of the positioning of the patient in the imaging system and what they expect to be observable in the resultant images. Some teaching practice asks students to simulate the imaging procedure in role plays – a student to be a patient and the other as the radiologist. The major drawback in the exercise is in the fact that an actual radiographic image cannot be obtained due to radiation risk. The learning experience is also limited by the availability of relevant images. Computer simulations overcome many inconveniences in role plays. The two teaching methods are not mutually exclusive but complementing each other. The values of simulation in the medical education have been argued favorably in various disciplines,[7,15-18] and radiology.[19,20] Radiological simulation packages have been developed for the purpose.[20-23]

In general, there are several technologies commonly in use for simulations: motion tracking, mannequins, image libraries, and synthetic images. Our aim is to give the students a flexible, realistic, and interactive learning environment without exposure to radiation. We are proposing a new concept in radiology simulation that combines physical and virtual reality. For example, if a student is taking an image of the wrist a patient, we want him to “take images” of the hand in different orientations in the imaging system. Different features of the wrist are observable with these orientations. Therefore, there are two aspects of the simulation – physical positioning of the patient and the X-ray images obtained from the position. The following is a short description of the candidate technologies for the purpose of mixed reality simulation – motion tracking of markers and mannequins for patient positioning; image libraries and synthetic radiography for image generation.

1 Motion Tracking

Motion tracking has been used successfully in movie production and computer game developments.[24,25] Markers are placed at the joints of an actor, and his motion is captured by the camera.

Placing the markers on the student can provide the positioning data to a computer for radiographic image generation. The advantage in this technology is that the students will develop the empathy for the patient because they personally tried out the position. The drawback is in the system setup that will require time and great care. This may be impractical even for a small class of students.

2 Mannequins

Besides automobile safety studies, mannequins have also been used extensively in medical education simulations, for examples, in obstetric trainings,[26] the Harvey mannequin in cardiology training,[27] the Gas Man[28] and the Comprehensive Anesthesia Simulation Environment[29] in anesthesia. Interested readers may find excellent reviews of mannequin applications in medical training in references.[26,30] Since we want a realistic simulation, we need a life-size dummy with flexible joints that are similar to human joints. Car safety studies have been using such dummies for many years.[31]

For our purpose, the dummy should have a realistic human form and features including some soft tissues. Realistic internal structures are not needed, but a few anatomical landmarks that can be felt on the skin, such as the base of the skull and the tip of the pelvis, are essential. Ideally, the dummy must be light enough for manipulation by one or two people without lifting devices. Sensors inside the dummy will supply the position and the orientation of all the joints to a connected computer. From these data, the computer will ‘generate’ the corresponding X-ray images.

3 Synthetic Radiography

The second approach is to have a computational human model whose posture is made according to the dummy’s data. Then, a simulation of the X-ray through the computational model generates the radiographic image. The technology required in the computational model approach is tangible. Accurate computational human models with organs and tissues are have been used in radiological studies for many years.[32-36] The posture of all these models is limited to the supine position that is the position of the CT and magnetic resonance imaging (MRI) scans.

Unlike animations in movies and computer games that require external features of a character but not the anatomically correct structures inside, a computational model for radiological imaging demands anatomical details. Such details move and deform with the posture. Recent developments have shown possible techniques.[37] Furthermore, new modeling techniques and increased computing power allow the generation of simulated images from computational phantoms directly.[38] Along the same line of study are the simulations of CT, positron emission tomography (PET) and single photon emission CT scans. The mannequin will be lying on the couch that can extend through the borehole of a mock-up scanner. In these cases, the position of the couch is also required.

4 System Design

Figure 1 is a schematic drawing of the system. The mannequin [part 1 of Figure 1] has realistic external shape and flexible joints with rotation/position sensors.

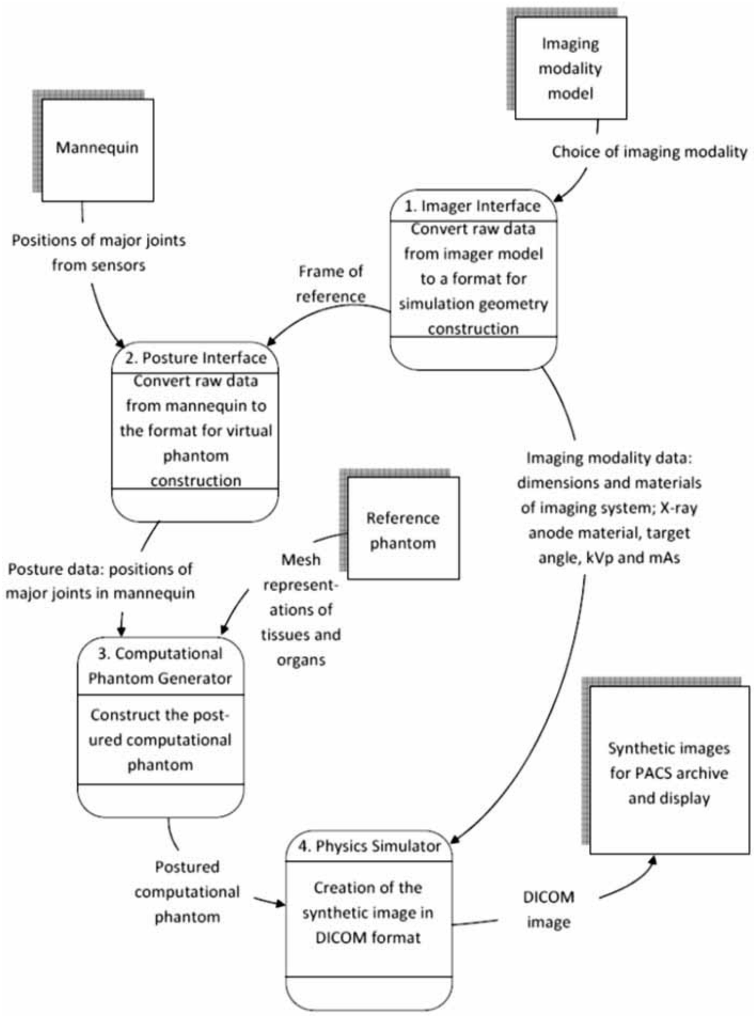

Figure 2: Data flow diagram of the proposed interactive simulation system. The reference phantom is generated only once for the corresponding mannequin, but it starting point for creating the postured phantom.

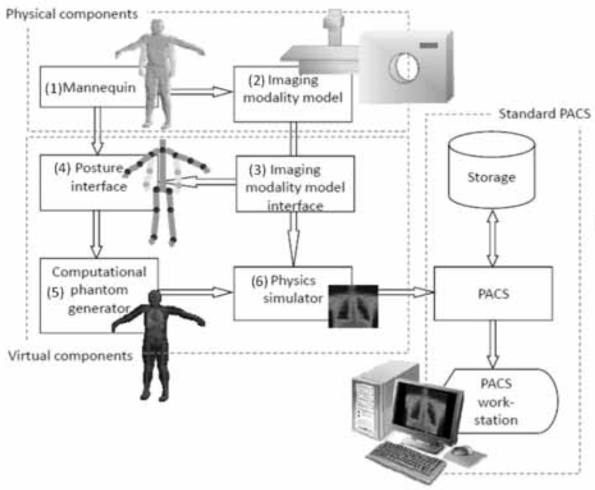

Figure 1: Schematic drawing of the proposed interactive simulation system. The mannequin and the imaging modality model are the physical components of the system. The data from these components are fed into the virtual parts that carry out the simulations with a computational phantom. The simulated images can be stored, displayed, and analyzed with picture archiving and communication system.

The angular/positional data are fed into the posture interface [part 2 of Figure 1] that tracks and displays the mannequin's posture. When the mannequin is ready for imaging, the computational phantom generator [part 3 of Figure 1] builds the phantom according to the posture. This computational phantom will be available to the physics simulator [part 5 of Figure 1]. Furthermore, the mannequin is positioned in an imaging modality model [part 4 of Figure 1]. The mannequin's position relative to the imager and the imager settings is also supplied to the physics simulator. The imager's settings include X-ray generator and detector characteristics. The physics simulator constructs the simulation geometry and tracks the X-ray photons from generation in the X-ray generator to their absorption in the detector. In the case of three-dimensional modality simulations, volumetric images are also reconstructed.

The images will conform to the Digital Imaging and Communications in Medicine (DICOM) standard so that integration with a fully functional picture archiving and communication system (PACS) is possible. The DICOM standard and the PACS systems are used extensively in a clinical environment.

In the case of simple X-ray imaging of the extremities, partially constructed mannequin corresponding to the extremity in question can be used. In the case of PET simulations, the image modality model will not supply the X-ray tube details. It will allow the user to enter the pharmaceutical information. This information will be available to the physics simulation. The use of the simulation system is described with the data flow diagram illustrated in Figure 2.

In the cases of PET simulations, the description of the source starts with the distribution of the radionuclides in the body instead of the description of the X-ray source. However, the manipulation of the mannequin, the generation of the postured computational phantom, and the physics simulation remain essentially the same as CT and other X-ray imaging simulations.

4.1 Mannequin

The mannequin [part 1 of Figure 1] is composed of a light-weight aluminum skeleton structure and a polysilicon skin, giving a realistic external shape of a person. Anatomical landmarks are attached to the aluminum skeleton. They can be felt by the user through the soft polysilicon skin.

The skeleton structure is connected by multiple-axis joints with rotation sensors and/or radio frequency (RF) transmitter. The locations of these joints correspond to the following joints in a human skeleton – the cervix between the base of the skull and the spinal column, shoulders, elbows, wrists, hip joints, knees, and ankles. The rotation sensors are connected to the computer system via cables or wireless system. The mannequin is manipulated by the user into the imaging modality model and in a posture suitable for the modality. The angular information of each sensor is fed to the posture interface. Position data received from the RF transmitters also allow the posture interface to deduce the mannequin's position in the imaging modality model.

4.2 Imaging modality model interface

The imaging modality model interface [part 2 and 3 of Figure 1] accepts input of the imaging parameters from the user. The parameters include filtration, tube voltage, and tube current of the X-ray generator in the case of simulating the X-ray-based imaging modalities or type of radiopharmaceutical and its concentration in the case of simulating nuclear medicine procedures. These data are supplied to the physics simulator for generation of virtual radiation particles. The control of these functions can be incorporated into the graphic user interface (GUI). The GUI also can reflect specific look and shape that of standard normal digital X-ray or other modalities accordingly. The GUI thus familiarizes the student for the GUI system on the real modality in a clinical environment.

Posture interface. The posture interface [part 4 of Figure 1] reads in the data from the rotation sensors and/or RF position system. A stylized visual representation of the mannequin and the imaging modality model are displayed on the screen for the benefit of the user. When the user is satisfied with the simulation configuration that includes the mannequin posture data and the imaging parameters, the posture interface will forward the data to the computational phantom generator and the physics simulator.

Computational phantom generator. The function of the computational phantom generator [part 5 of Figure 1] is, as its name implies, to construct a computational phantom. The construction starts with the data from the posture interface which provides the information of the selected joints in the mannequin.

This is also the information on the corresponding joints in the computational phantom. Thus, the computational phantom generator has a built-in reference phantom. This reference phantom is created from CT/MRI scans of a real patient in a supine position [Figure 3].

The three-dimensional image is segmented so that tissues and organs are individually identified. The mannequin's dimensions and joint positions are derived from this reference phantom so that the selected joints in mannequin reflect those in the reference phantom. Furthermore, the morphology of mannequin skin is also derived from the reference phantom.

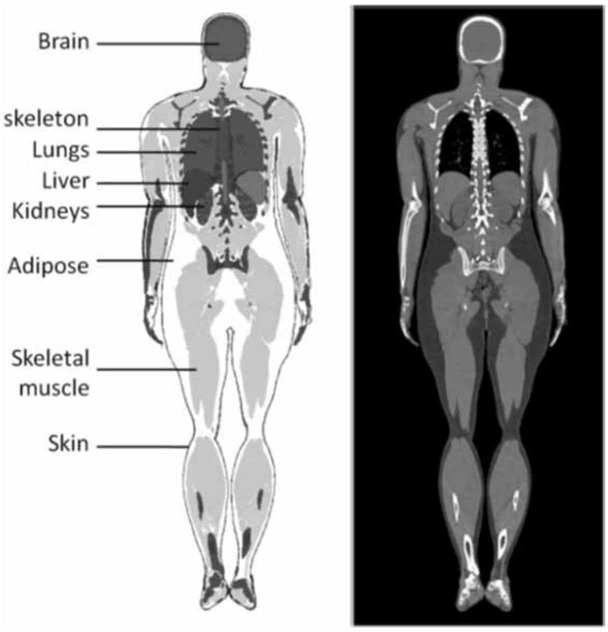

Figure 3: A voxel phantom (left) created from a computed tomography image (right). Each tissue is labeled by a number (tissue ID) after segmentation. In this coronal cross section of the phantom, the tissue IDs are plotted in different colors. There are about 100 identified tissues or organs in the phantom; only a few of them are shown here for illustration.

Creation of the built-in reference phantom. The reference phantom is created by segmenting the CT/MRI images. Triangular meshes [Figure 4] are generated to delineate the major organ and tissue outlines, including bones and skin as well.

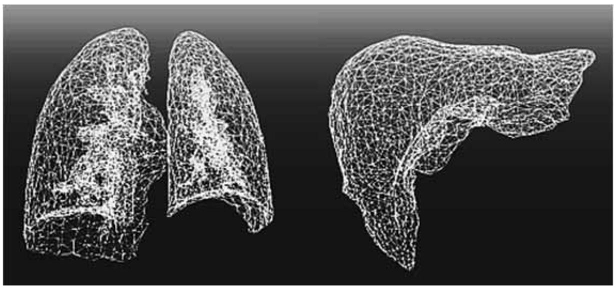

Figure 4: Mesh representation of the lungs (left) and the liver (right).

This constitutes the set of complete morphological data. Then, a reduced morphological data set is constructed. This reduced data set consists of the meshes of the bones and the external skin outline.

A process known as skinning and rigging [39] is applied to the bone and skin meshes such that the skin mesh is attached directly to the bone meshes. The process is a computer graphic technique used extensively in game and movie industries. In cases of suitable patient scan is not available, another method for the phantom generation can be used, e.g., NURBS-based.[40]

Generation of the posture phantom. Starting with the reduced morphological data and from the joint positions and orientations, the computational phantom generator maps the skeleton to the posture of the mannequin. Since the skin is attached to the skeleton directly in this data set, the skin mesh of the reference phantom is deformed accordingly. This creates a simplified posture phantom with bones and skin only. Then the deformation of internal organs and tissues in the complete morphological data is interpolated from this simplified phantom to obtain the detailed posture phantom. The last step is to voxelize the detailed posture phantom and to associate each voxel with elemental composition and density of the tissue of the voxel.[41] The elemental compositions and densities are coming from literature. This voxelized phantom is the computational phantom required in the subsequent physics simulations.

Major software graphic user interface modules. In addition to the basic function of any given GUI here, it can play a role in aiding the education process when using such simulation system. GUI modules can introduce the student to the theoretical part of the imaging process. The GUI functions are to control the workflow of the simulation system, invoke the posture interface, imaging modality GUI interface and physics simulator GUI interface. Imaging modality GUIs interfaces accept the imaging parameters such as kilovotage peak (kVp) and (mAs) in X-ray-based modalities. In the case of radionuclide distribution modality like in PET, the GUI provides the control of another related parameter such as detector material and pixel dimensions from the user. It is possible that certain information like the distance between the X-ray source and the detector can be obtained automatically from the imaging modality model. In the initial development stages, we might want this to be entered through the GUI.

5 Physics Simulator

The physics simulator [part 6 of Figure 1] uses the data from the imaging modality model to create the appropriate models of the radiation source and detectors. It generates and tracks virtual radiation particles through the imager and computational phantom geometry.

The particle generation depends on the radiation source. In the case of simulating X-ray-based imaging modalities such as CT, chest X-ray, dental X-ray, knee X-ray, and others, the anode-filter combinations are taken into account. The user chooses the tube potential (kVp) and current (mAs). In the case of nuclear medicine-based imaging modalities, the type of radioisotope, its activity, and distribution in the body are specified by the user. Thus, the physics simulator is generating the virtual photons at energies, positions, and directions relevant to the study.

The simulator then tracks the photons through the geometry using a combination of Monte Carlo and deterministic techniques. In the process, the radiation physics relevant to diagnostic imaging are taken into account. They include photoelectric absorption, Rayleigh scattering, and Compton scattering. Figure 5 shows a typical Monte Carlo process.

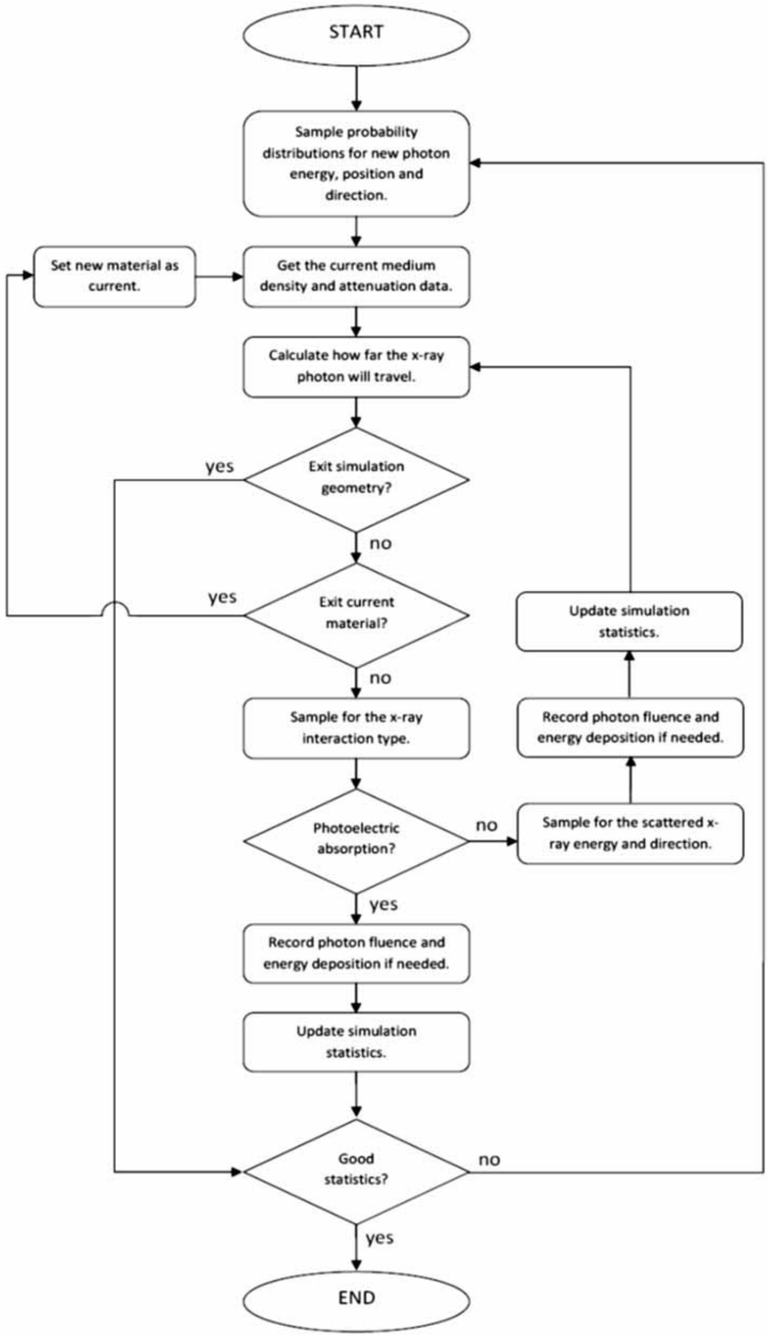

Figure 5: The Monte Carlo process to track one virtual X-ray photon. The process is repeated as many times as necessary to synthesize the image. It is important to note that the virtual photons must be independent of each other, that is, the sequence of random number in the sampling of the probability distributions cannot repeat itself in the simulation.

For a virtual photon at the source location, the simulation engine computes how far the photon will travel before interaction. Then it will determine the type of interaction and its outcome by sampling appropriate probability distributions from physics.

Each time the X-ray photon crosses from one material to another, the simulation engine will fetch the correct probability distributions for the new material and start tracking by computing how far from the boundary that the photon will go. If the photon enters the imaging detector, a score will be registered the process is continued until a sufficient number of photon satisfy the statistical benchmark of slandered Monte Carlo code scoring criteria.

Since the image is generated from the scoring of the virtual photons arriving at the imager, realistic images can be created so that students can observe the effect of patient posture and their choice of radiation source and imager. Each image is synthesized under a unique setting. Observable features differ in each image. Students can thus familiarize themselves with the choice of anode-filter combination, kVp and mAs settings in X-ray-based imaging and radioisotopes and their activities in the cases of nuclear medicine. Figure 6 contains several synthetic X-ray images of the reference computational phantom in [Figure 3] different X-ray energies and orientation. Volumetric images (for example, CT and PET) are also reconstructed from the scores. All images are converted into DICOM format for storage and display by PACS.

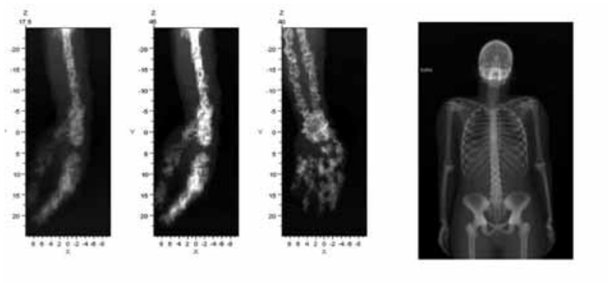

Figure 6: Synthetic X-ray images of the wrist of a low-resolution voxel phantom [36] and upper torso from the voxel phantom shown in Figure 3.

6 Discussion

In medical education, there is a concept of standard patient who is a person trained to pretend to be a patient. The standard patients provide uniform training to and unbiased assessment of the trainee physicians. In fact, simulation is becoming an integral part of the accreditation process in several medical disciplines.[15,17,42]

Our proposed interactive simulation system offers the radiological science trainees as the standard patient to trainee physicians. Although the mannequin would not be able to position itself automatically like a real person, abnormalities could be embedded in the computational phantom. Synthetic images with these abnormalities are possible.

The ability of the simulating abnormalities depends on the available computational power and resolution of the computational phantom. As an example, small fractures in bones might be difficult to model and impossible to simulate with a phantom of large voxels. On the other hand, small fractures can be simulated with a stylized mathematical model. Developing a phantom that support the simulation of small features will be a challenge. Techniques have been developed to address the challenge in the simulations of tumors and microcalcifications in the breast.[43-45] Such techniques are transferable to other radiological abnormalities. Further progress will be made in this aspect in the next stage of the simulation system development.

Radiation risk is a major concern in the career of a radiological technologist or scientist. This is especially true during training. The students might be preoccupied by the unfamiliar equipment and therefore paying insufficient attention to radiation safety. The proposed system attacks this issue on two fronts. First of all, there is no radiation involved physically. All types of radiation are occurring in the virtual world. The students are not exposed to the radiation. Any mistakes will not incur radiation exposure to the students. Second, radiation dose calculation can be carried out in real time as the radiation particles are tracked in the Monte Carlo simulations as the synthetic images are generated.

Without worries of radiation, the students will be able to familiarize themselves with the equipment at their own pace and in their own time. Effects of patient position and settings of the imaging equipment on the resultant image are available to the students immediately. Results can be archived for further analysis.[20] Student performance can be monitored online. Minimal supervision will be required from the educator. Clinics and hospitals can make better and more effective use of the resources for the benefit of the patients. These invaluable resources include clinicians and equipment.

When the students enter the real clinical environment for the 1st time, they are expected to have mastered the basic skills with respect to the equipment and radiation safety. They are also expected to understand the positioning aspects when dealing with a real patient. They have mastered those skills without any radiation exposure and without using up valuable clinical resources. Another advantage of the system comes from the versatility of the Monte Carlo method. Although PET and X-ray procedures are very different equipment-wise and clinically, the codes to track the radiation particles are the same. Thus, the simulation system can easily be expanded to include various radiological trainings in CT, nuclear medicine, radiotherapy, and others. More technical consideration can be found in.[46]

7 Conclusion

The idea and the design of an interactive simulation in radiological education have been presented, highlighting the software aspects of the system. This is an ongoing project where the system itself currently under development and prototyping. The hardware integration will be presented in a separate paper. The complete system consists of physical mannequins and models of imaging equipment that link to a computing system and PACS. The computing system carries out simulations in real time according to the setting of the mannequin and the imaging equipment model while the PACS displays and archives the synthetic images.

Monte Carlo simulations are inherently time-consuming but parallel processing is available even in a desktop computer nowadays. With parallelized Monte Carlo codes to take advantage of the multicore processors, the time required to generate a synthetic X-ray image can be achieved within seconds. Real-time online simulation in the system is a reality. The computational phantom is intrinsically linked to the physical mannequin in shape and dimensions. It is possible to create mannequins and computational phantoms representing patients of different size, shape, gender, and age. The presence of the physical model enhances the realism. The students can see and feel the "patient" and the imager and correlate patient positioning with the final image.

Together with dose calculations and tutor's immediate feedback, the proposed system will give students interactive and realistic learning experience. Most importantly, students can experiment with a practically unlimited number of possibilities without any risk or fear of radiation exposure. Extension of the system to other radiological science disciplines can also be achieved easily because the computation engines (Monte Carlo and others) remain the same regardless the application. A patent of the system has been granted.[46]

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