




Projectional Radiography Simulator: an Interactive Teaching Tool

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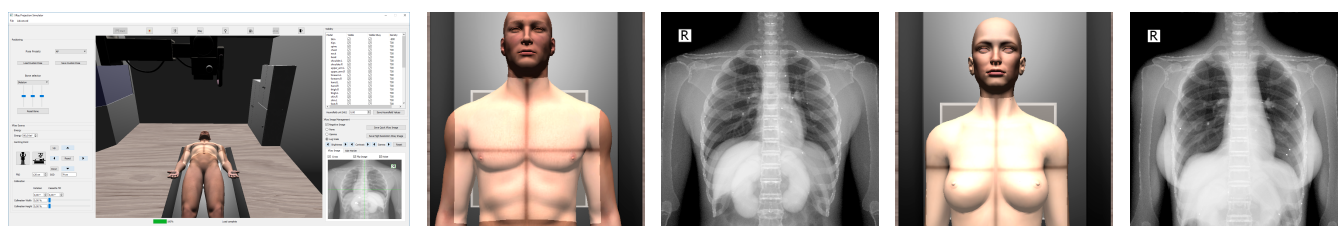


Figure 1: Results obtained using different anatomical models.

Abstract

Radiographers need to know a broad range of knowledge about X-ray radiography, which can be specific to each part of the body. Due to the harmfulness of the ionising radiation used, teaching and training using real patients is not ethical. Students have limited access to real X-ray rooms and anatomic phantoms during their studies. Books, and now web apps, containing a set of static pictures are then often used to illustrate clinical cases. In this study, we have built an Interactive X-ray Projectional Simulator using a deformation algorithm with a real-time X-ray image simulator. Users can load various anatomic models and the tool enables virtual model positioning in order to set a specific position and see the corresponding X-ray image. It allows teachers to simulate any particular X-ray projection in a lecturing environment without using real patients and avoiding any kind of radiation risk. This tool also allows the students to reproduce the important parameters of a real X-ray machine in a safe environment. We have performed a face and content validation in which our tool proves to be realistic (72% of the participants agreed that the simulations are visually realistic), useful (67%) and suitable (78%) for teaching X-ray radiography.

CCS Concepts

• **Computing methodologies** → Simulation types and techniques; Animation; Rendering; Virtual reality;

1. Introduction

Medical simulators provide a secure environment where trainees can spend their time testing and improving their abilities. Not only for the patient, also some medical procedures are risky for professionals such as radiographers due to the use of ionising radiation. A very common medical imaging modality is *projectional radiography* (also called *projection radiography*, and *X-ray radiography*), where two-dimensional images are produced using X-ray radiation. Projectional radiography helps physicians to diagnose diseases or injuries as bone fractures, etc. Each specific location along the body requires a correct patient positioning and X-ray machine configuration. Important aspects of the procedure (including positioning, centring, collimation of the X-ray source, voltage of the X-ray tube, time of exposure, distance source to patient, and distance source to

detector or film) must be performed accurately to perform a safe image acquisition. We present an X-ray projectional radiography simulator where users can interactively train with real-time animation of the anatomy and real-time framework for the simulation of X-ray images. They can modify patients' postures and X-ray machine parameters in order to visualise the corresponding changes in the X-ray radiographs.

Our tool was designed to meet the following requirements: (i) The system must be able to make use of off the shelf virtual patient models. (ii) Users may interactively manipulate the virtual patient to the position required in any given procedure. (iii) Users may observe the X-ray image immediately as they change the virtual patient's position, X-ray source's position or any other X-ray machine parameter.

To fulfil the requirements mentioned above, our application relies on two modules: the Virtual X-ray Imaging Library (gVirtualXRay) [VV16] and the Virtual Patient Positioning System (VPPS) [SCSG18]. The first one is in charge of generating the X-ray images from triangular meshes in real-time. This module can take into account most of the relevant X-ray configuration parameters. It is available as an open source project written in C++, with wrappers to other popular programming languages, including Java, C#, Python, R and Ruby. The VPPS transforms the anatomy of a virtual patient to the desired position. It was designed to be flexible to deal with as many virtual patients as possible. With this goal in mind, our algorithm works with incomplete anatomical models (skin and bones are the only anatomical structures that are required) and biomechanical properties of the virtual patient tissues are not required. Finally, both modules are integrated into a courseware environment, which implements the user interface and characterises the most important steps in X-ray projectional radiography. A face and content validation study has been eventually conducted to assess the realism and usefulness of our software as a teaching tool that can be used in the classroom.

2. Projectional Radiography Training

Projectional radiography training combines theory and clinical practice. Undergraduate students in radiography must master theoretical information such as anatomy and radiation physics before they could move on to a clinical environment. To experience what they have learnt in lectures, trainees may practice in a separate session the use of X-ray machines on anatomical phantoms to see the effect of imaging principles, a practice that could not be performed on living tissue. This leads to a disconnect between theory and practice. In addition, teaching cases are used. They show patient histories with the corresponding medical images and recorded discussions. Each institution often gathers their own repositories. However, online public resources are becoming available where radiographers consult a vast set of patient histories [DRB*17] and even mobile phone apps have been created [Spo17]. Nevertheless, these images are static and there is no exhaustive explanation about how they were taken. Also, it is not possible to modify any acquisition parameter (e.g. tube voltage) or to visualise more X-ray radiographs from the same patient. Furthermore, patient positioning is a key step of the procedure and there is no image of the real patient that gives some idea of the correspondence between both.

Simulators can provide a safe place where trainees could replicate all they learnt in order to bridge the disconnects between theory and practice. medspace.VR [BGK*14] is an interactive tool that simulates the complete procedure. Although it allows animating the patient, internal tissues do not seem to be present and there is a lack of variety in the anatomic models.

3. Visual Computing for an X-ray Radiography Teaching Tool

Virtual patient animation. VPPS extends the classical skeletal animation pipeline based on skinning to deal with the deformation of internal tissues. This algorithm was designed to adapt a virtual patient to the pose required in a given medical procedure interactively. We have adapted each step to deal with volumetric meshes in

order to consider the influence of the bone's tissues in the character deformation. Instead of calculating the weights onto the model's surface, we discretise the internal space into a tetrahedral mesh. We compute a displacement field inside the virtual character. This field transforms the tetrahedral mesh using a skinning technique and they are used to animate the character's tissue vertices using barycentric coordinates. Consequently, this field can be applied to both the B-Rep and volumetric models. The animation pipeline is divided into the following successive stages (see Figure 2):

Rigging: Our technique adjusts a predefined virtual skeleton to the character's bones instead of guessing a virtual skeleton based on the skin mesh. The algorithm uses the bones' models to guess the rotation centre of each joint of the virtual skeleton.

Tetrahedralization: In this step, we generate an internal tetrahedral mesh from the skin and bone models. This volumetric mesh will be used to define a continuous displacement field associated with the movement of the bones.

Weighting: With this tetrahedral mesh, we compute the weighting phase taking the bone geometry into consideration. This stage calculates automatically the influence of each bone on the tetrahedral mesh vertices.

Mapping: All internal tissues meshes are assigned to the tetrahedrons of the volumetric mesh and their barycentric coordinates are calculated.

Optimised Centres of Rotation This step is specific from CoR [LH16] skinning technique. We calculate a centre of rotation for each tetrahedron's vertex.

Pose selection and skinning: In this step, the movements of the virtual skeleton are transferred to the tetrahedral mesh using a standard skinning algorithm such as LBS [MTLT88], DQS [KCvO07] or CoR. Then, the tetrahedral mesh movements are applied to the tissues models. In our system, the user interactively selects the virtual character pose. Nevertheless, other techniques such as motion capture systems can also be used.

The rigging, the tetrahedralization, the weighting, the mapping and the computation of the rotation centres are computationally expensive. They are performed as an automatic preprocess stage, which must be executed only once per virtual patient. This way the positioning selection and the skinning can run at interactive rates.

X-ray Simulation. gVirtualXRay implements the L-buffer principle [FDLB06] on the GPU [VV16]. It computes the path length of X-rays, from the X-ray source to every pixel of the detector, using the programmable graphics pipeline of the GPU. It detects all the intersections between the path of X-rays and the polygon meshes, then solves the Beer-Lambert law (also known as attenuation law). gVirtualXRay relies on Hounsfield values and converts them into mass attenuation coefficients and densities according to the material composition of the anatomical tissues [SBS00]. In this way, gVirtualXRay simulates radiographs on the graphics processing unit (GPU) in milliseconds.

As both VPPS and gVirtualXRay rely on polygon meshes, when the virtual patient is loaded into the simulator, both modules share the same anatomic tissues in the GPU's memory.

Courseware. We have created a courseware module, which is in charge of developing the teaching and training capabilities of the

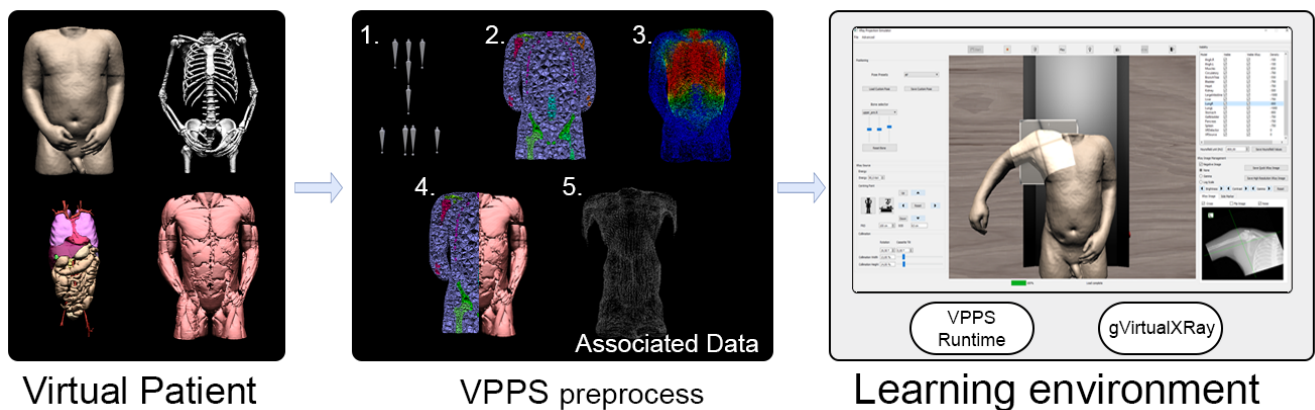


Figure 2: Algorithm overview. The preprocess module runs once per model: 1. Rigging, 2. Tetrahedralization, 3. Weighting, 4. Mapping, and 5. Optimised Centres of Rotation. The X-ray simulator loads the patient anatomy, the precomputed data, and the X-ray acquisition parameter to generate the corresponding X-ray image.

simulator. It unites both modules and provides a graphical user interface (GUI). We will describe below its most important features in order to replicate a projectional radiography procedure.

The positioning of a patient is crucial to retrieve the X-ray image from the target anatomy. First, users have to choose whether the patient will be standing up or lying down. Through the GUI, users are able to move any joint available in the model in three ways: (i) Using pre-set positions. (ii) Using forward kinematics (selecting joints in the GUI and rotating them). (iii) Using motion capture with the Microsoft Kinect (see <https://youtu.be/1s-eTT1pCy8> for evidence).

Second, *Centring point* is a technical term that is referred to the focus point of the primary X-ray beam in relation to anatomy. Centring and positioning of the patient are heavily correlated and they define the relative positions of the X-ray source, of the cassette and of the patient. After the patient positioning stage, users have to adjust the position of the X-ray source and cassette. GUI buttons allow users to finely tune the centring position. Similarly to real X-ray machines, a cross is projected on the the patient' skin using a visible light source to represent the X-ray beam (see dark crosses on the anatomical models in see Figure 1).

Regarding the X-ray setup, three components must be configured: (i) The *X-ray source* is defined by its position, shape (e.g. parallel beam, point source, or focal spot) and beam spectrum (monochromatic or polychromatic). (ii) The *X-ray detector* (or cassette) is defined by its position, size, resolution and orientation. (iii) *Each anatomical structure* is defined by a triangular mesh and its material properties to compute linear attenuation coefficients. Users must select the relative distance between the X-ray source and the detector or cassette (known as *source to image distance (SID)*) or the distance between the X-ray source and the patient (known as *source to object distance (SOD)*).

Collimation is another common technical term used in radiography. Lead plates or leaves are used to limit the exposure to ionising radiation to a given area of the body and it is placed at the front of

the X-ray tube. Our system allows users to adjust the collimation of the anatomic area of interest.

Finally, an anatomical marker is placed in the radiography to identify the left- and right-hand sides of the patient. This practice is compulsory in clinical radiography. Users can place it within the field of the X-ray source using the corresponding GUI widget.

Finally, our simulator implements a small digital imaging manipulation toolkit. Digital X-ray detectors are used in modern hospitals rather than traditional X-ray film. This allows capturing the X-ray image directly to a bitmap, and it is possible to display it using a computer. The greatest advantage of digital imaging is to reduce minor problems due to overexposure or underexposure. Users can use the GUI to manipulate the X-ray image and to enhance resulting images. See the following video for further details: <https://youtu.be/WFOAVSLXufs>.

Lecturing and Training Features. We have developed additional features that are not directly related to any step of the diagnostic radiography procedure. These features support the instructor in the classroom environment. The courseware allows to show and hide specific tissues of the virtual patient. It also allows the teacher to show the relationship between the different body tissues and X-ray images. Teachers can modify the tissues properties using the Hounsfield Scale to show a variety of diseases, e.g. a calcified bone, a collapsed lung, or an air-filled stomach. Additionally, teachers can introduce foreign objects inside the internal anatomy.

Besides, the courseware offers a non-guided exercise mode. Students are asked to replicate a list of projections designed by their teachers. The simulator retrieves assessment metrics that allows the instructors to check the evolution of the trainees. See the following video <https://youtu.be/GwWY8AQffEY> for an illustration of the courseware.

4. Results

We have tested the computational performance of our software on several anatomical models, including the ZygoteBody™ Male and Female Models [Zyg18] (see Figure 1), and Voxel-Man's Segmented Inner Organs [TPP*02] (see Figure 2). The most complex case, ZygoteBody™ Male, is made of 8×10^5 vertices and 1.5×10^6 triangles, and generates 3.5×10^6 tetrahedrons.

Such simulators require interactive frame rates to guaranty an adequate user experience. Our simulator runs over 30 fps with the ZygoteBody™ model. This is possible because the pre-processing module executes the expensive steps and generates auxiliary data. It requires less than 7 minutes for each virtual patient.

5. Face and Content Validation

We have conducted a combined face and content validation to gather feedback from experts. 14 statements related to the realism of the simulator and its functionalities were used for the face validity. For the content validity, 11 statements related to the main purpose of the simulator and the courseware were included. The survey can be consulted at <https://goo.gl/forms/Pv3F7Aqjb3VG80b73>. 18 well-experienced participants were recruited. The average number of years of experience is 12.5 years, the standard deviation is 11.74 years. Most participants were from the United Kingdom (15 of them), 1 participant was from Canada, 1 from France, and 1 from Spain. The percentage of 'strongly agree' or 'agree' answers for each statement is above 50%. The results show that our tool is realistic in many ways (72% of the participants agreed that the simulations are visually realistic), useful (67%) and suitable (78%) for teaching X-ray radiography. This is promising because participants believe that our tool is realistic, useful and suitable to teach and/or learn X-ray radiography.

6. Discussion and Conclusions

We have designed an interactive X-ray radiography learning environment to assist teachers during lectures and for self-directed learning. Its main aims are to reduce the gap between theory and practice, to allow repetitions and mistakes without any radiation risk. In contrast with static cases and images from books, teachers and students can interactively experiment the effects of good and bad practices. Our simulator accepts any third party models as long as the skin and bone tissues of the virtual patient are properly labelled.

As a result of using a geometrically-based algorithm, the positioning system sacrifices accuracy in favour of computational performance and flexibility. It provides a heuristic solution and would not be suitable for surgical planning. As future work, the positioning algorithm could be improved. The use of gVirtualXRay has proven effective to generate X-ray radiographs. Our project could be extended to simulate data from other imaging modalities such as magnetic resonance imaging (MRI) or computed tomography (CT).

The overall validation study shows the usefulness and suitability of our tool in teaching and/or learning X-ray radiography. Further tests would be needed to perform a construct validation study.

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