Workflow for creation and evaluation of
virtual nephrolithotomy training models

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ABSTRACT

PURPOSE: Virtual reality (VR) simulation is an effective training system for medical residents, allowing them to gain and improve upon surgical skills in a realistic environment while also receiving feedback on their performance. Percutaneous nephrolithotomy is the most common surgical treatment for the removal of renal stones. We propose a workflow to generate 3D soft tissue and bone models from computed tomography (CT) images, to be used and validated in a VR nephrolithotomy simulator.

METHODS: Venous, delay, non-contrast, and full body CT scans were registered and segmented to generate 3D models of the abdominal organs, skin, and bone. These models were decimated and re-meshed into low-polygon versions while maintaining anatomical accuracy. The models were integrated into a nephrolithotomy simulator with haptic feedback and scoring metrics. Urology surgical experts assessed the simulator and its validity through a questionnaire based on a 5-point Likert scale.

RESULTS: The workflow produced soft tissue and bone models from patient CT scans, which were integrated into the simulator. Surgeon responses indicated level 3 and above for face validity and level 4 and above for all other aspects of medical simulation validity: content, construct, and criterion.

CONCLUSION: We designed an effective workflow to generate 3D models from CT scans using open source and modelling software. The low resolution of these models allowed integration in a VR simulator for visualization and haptic feedback, while anatomical accuracy was maintained.

KEYWORDS: Virtual Reality, simulation, 3D modelling, nephrolithotomy, segmentation

1. PURPOSE

Percutaneous nephrolithotomy is the most common surgical treatment which doctors perform to remove large renal stones. This type of endoscopic procedure requires surgeons to have skills in coordination and instrument handling. Major bleeding can occur in the patient's kidneys if the entry point puncture of the needle pierces the vessels found between the calyces instead of entering straight into the kidney duct system[1]. Although traditional physician-student relationships are the foundation of residency training programs, recently, virtual reality (VR) surgical simulators have gained considerable interest. These VR systems have allowed surgical residents to train in a more efficient and cost-effective process, acquiring more quantitative feedback from the technology and encountering fewer limitations regarding instructors or patients[2].

The value of training nephrolithotomy through a VR simulator is dependent on a realistic and accurate virtual environment. This requires the generation of soft tissue and bone models from real patient data. 3D Slicer is an open source platform that can be used to create segmentations from computed tomography (CT) scans through semi-automatic methods and manual editing[3]. Ensuring the virtual models react similarly to live human tissue requires collision detection to produce haptic feedback for the simulation. This allows the user to receive sensory feedback

when their surgical instruments contact the surface of the organs in the virtual environment[4,5]. Collision detection occurs on each polygon of a 3D model through an algorithm which computes the number of intersections between the tool objects and the triangulated mesh. Due to the quadratic time complexity of calculating these collisions, refining segmentations to low-polygon models is needed for an efficient haptic rendering process[6].

To confirm that a VR system is a realistic and useful training environment, validation studies are required. Validation of simulators commonly includes face, construct, content, and criterion validation. Face validation confirms the simulation's accuracy and realism, construct validation ensures the system can differentiate experience levels, content validation proves its usefulness as a training tool, and criterion validation refers to the simulator's ability to reflect and predict performance of the same procedure in an actual operating room[7].

Our study proposes a workflow to transform abdominal CT scans into low polygon 3D models to be integrated in the K181 PCNL and Kidney Access Array by Marion Surgical[i]. This system is a percutaneous VR surgical simulator for training nephrolithotomy access under real-time fluoroscopy. We integrate models generated through our workflow into the simulator. Experienced urological surgeons use the simulation system and evaluate the models on a 5-point Likert scale to determine validity.

2. METHODS

The requirements for the models that were to be integrated into the virtual simulator were based on anatomical accuracy and haptic efficiency. Unlike typical semi-automatic segmentations which possess high polygon surface mesh in order to achieve accuracy of edges and texture, the models we generated needed to have the minimal number of polygons. This ensured that the collision detection algorithm which produces haptic feedback would proceed at an efficient rate when the models were integrated into the simulator. Furthermore, the low polygon rendering of the models still needed to possess enough anatomical detail for the virtual environment to be a realistic simulation of the real operating room and patient.

2.1 Registration and Segmentation

St. Joseph's Healthcare Hamilton[ii] provided nephrolithiasis CT scans for our research purposes. We segmented the patient's abdominal CTs into major organs and bones using the Fast GrowCut algorithm through the *Grow from seeds* tool in the Segment Editor module of 3D Slicer. Major abdominal anatomical features were painted and labeled to act as the seeds. The *Grow from seeds* function then fills in the connected areas of each organ, blood vessel or bone. However, following this automatic region growing process, we still needed to perform manual qualitative editing of the segmentations through the paint, erase, and logical operator functionalities of Segment Editor, specifically ensuring that we generated accurate calyx and duct segmentations (Figure 1). To produce a visually realistic patient for the virtual environment, we registered full body CT scans[iii] to the original patient CTs (Figure 2) by placing fiducials on connecting spinal columns and muscles and using the SlicerIGT extension to calculate the fiducial registration[8]. We then segmented the spine, ribs

Figure 1: Initial segmentation of kidney calyx and duct (including renal stones).

(Figure 3), and skin/fat layer of the registered full body CT, exporting segmentations of kidney cortex, kidney calyx, duct system, bladder, liver, vein, artery, skin, and skeleton as models in OBJ files.
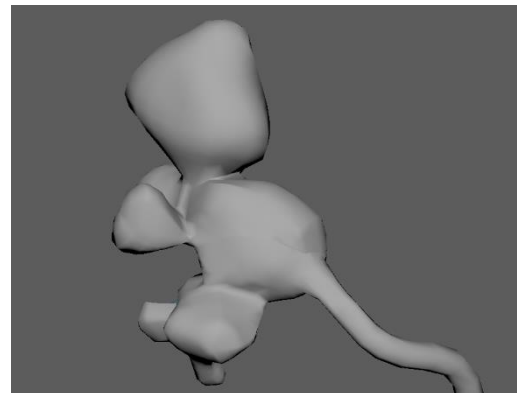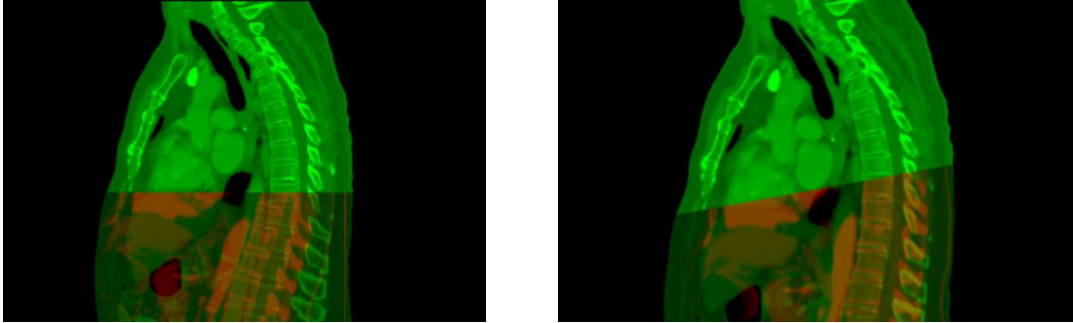
Figure 2: Red patient CT scan overlaid with green full body CT before (*left*) and after (*right*) fiducial registration.
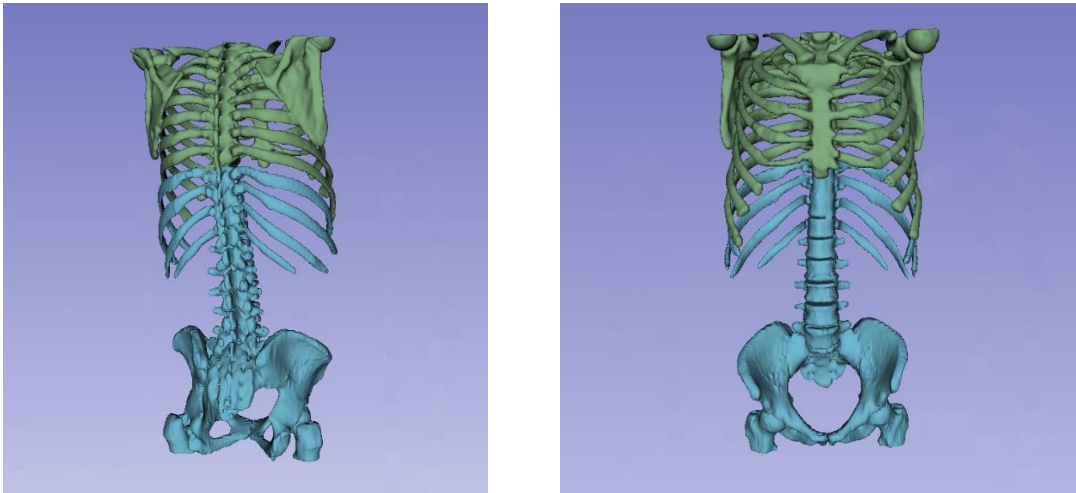

Figure 3: Segmentation of post-registration full body skeleton produced in 3D Slicer.

2.2 Re-Modelling and Decimation

Autodesk Maya modelling software[iv] was used to produce low polygon models of the abdominal organs. The low polygon versions of each segmentation were needed to provide an efficient haptic rendering process during integration into the simulator. The skeleton model was generated through automatic decimation of vertices by 87.5% (Figure 4).
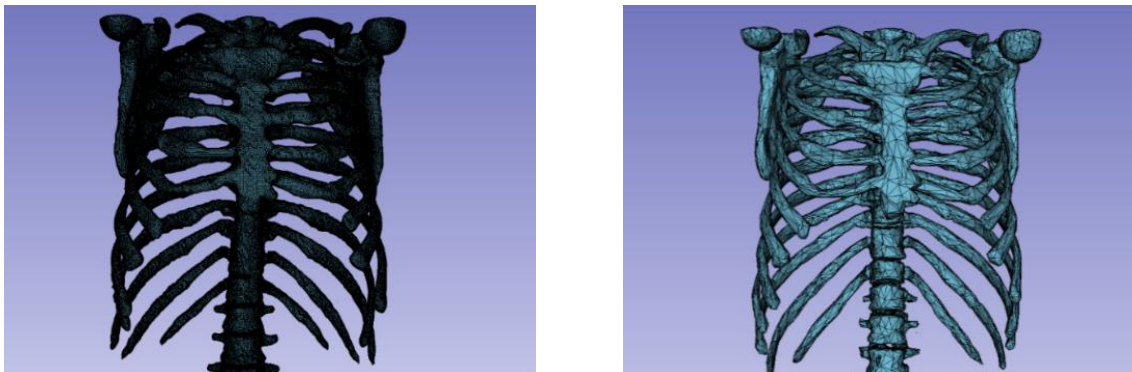

Figure 4: *Left.* Initial high polygon segmentation of skeleton showing edges. *Right.* Generated skeleton model showing edges after 87.5% vertex decimation.

[iv] https://www.autodesk.ca/en/products/maya

For the other organs, much higher preservation of specific anatomical details was required. Thus, we performed manual re-modelling of the structures to create the low polygon mesh versions of each organ: First, we placed curves along the surfaces of the original segmentations exported from 3D Slicer; then, using Maya's loft and extrude functions, we generated an initial outline and shape for the new models. To achieve further visual realism, we manually edited the vertices of the low polygon mesh to ensure the structures were sufficiently accurate to the original segmentations produced from the patient data (Figure 5).
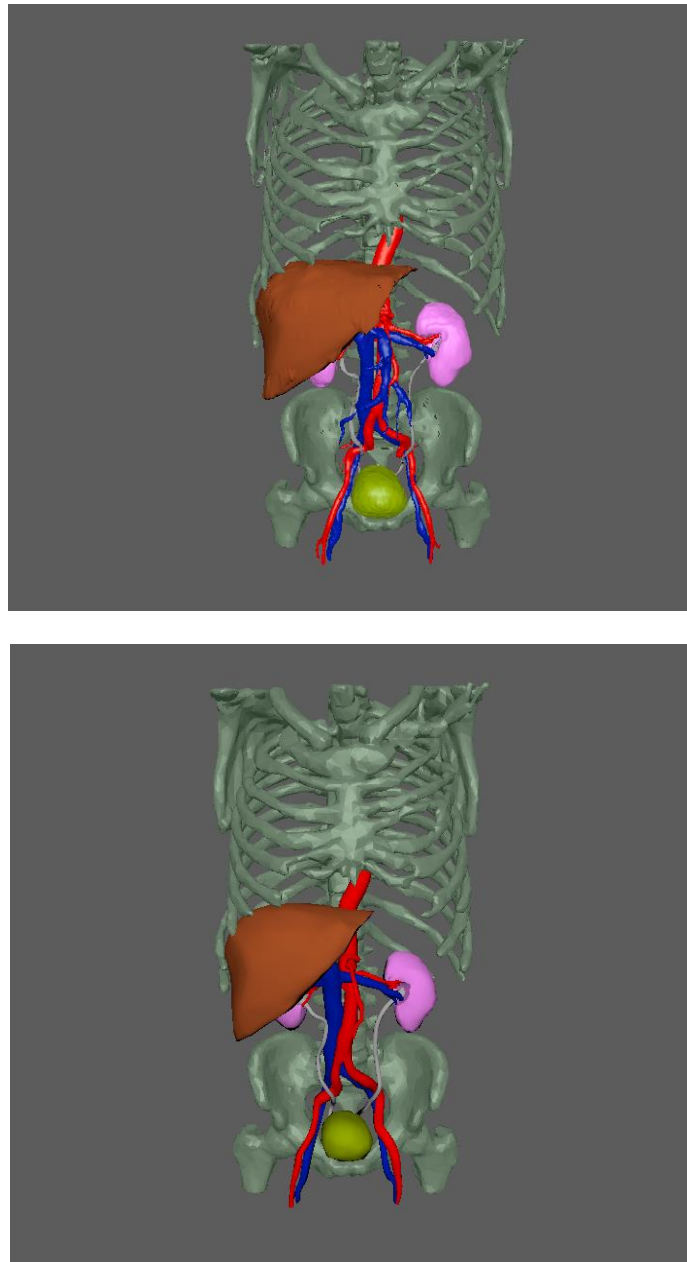

Figure 5: Comparison of high polygon segmentations (*Top*) and low polygon mesh models (*Bottom*).

2.3 Zoning of Kidney

For this simulated nephrolithotomy operation, the entry point on the surface of the kidney and the following trajectory through the calyx is tracked by the system to provide training scores after the user completes the procedure. For this function, we created models representing safe zones, warning zones, and danger zones based on information provided by urologists. These zones extend from the duct system to the kidney surface and were generated using Maya's extrude function (Figure 6).
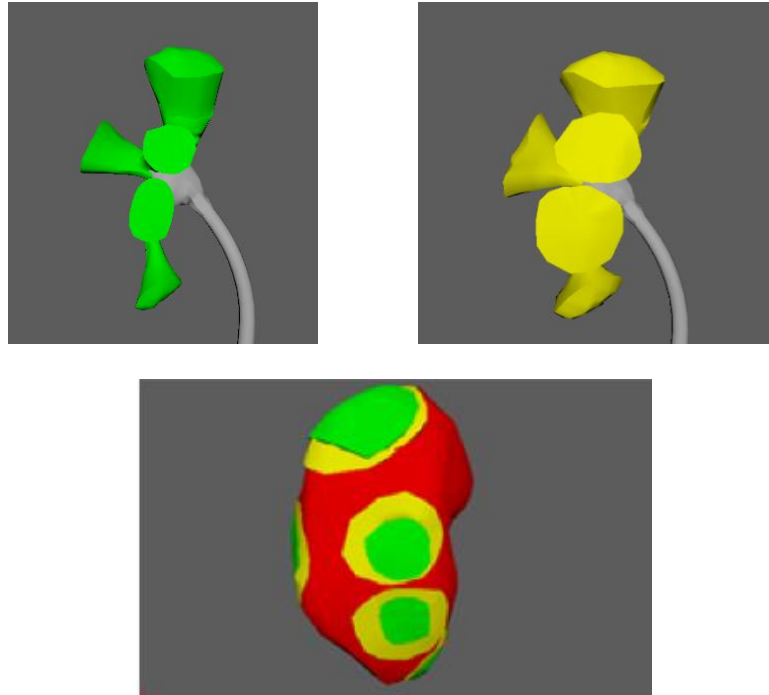

Figure 6: *Top Left.* Safe insertion zone connecting to duct. *Top Right.* Warning insertion zone connecting to duct. *Bottom.* Safe, warning, and danger zones displayed as the kidney surface.

2.4 Validation Testing

We integrated the models into the K181 PCNL and Kidney Access Array system. Scoring metrics were added using our generated safe, warning and danger zones to assess needle placement and insertion by the user. Testing of the model and procedure viability in VR was performed by two urological surgeons (Figure 7) who had each executed over 250 similar procedures in the operating room. Following their experience with the simulator, each surgeon completed a questionnaire based on evaluating the simulator's face, content, construct, and criterion validity.
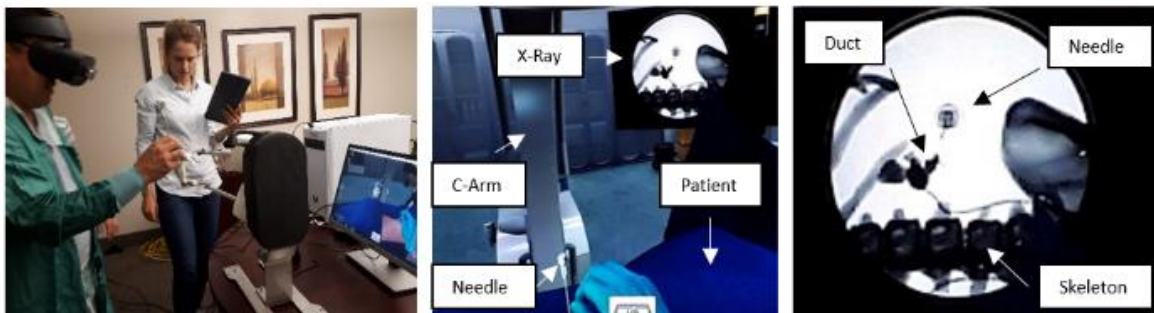

Figure 7: *Left.* Surgeon performing the procedure on the K181 PCNL VR simulator. *Middle.* Virtual surgical environment. *Right.* Close-up on fluoroscopy of needle, duct and skeleton in VR.
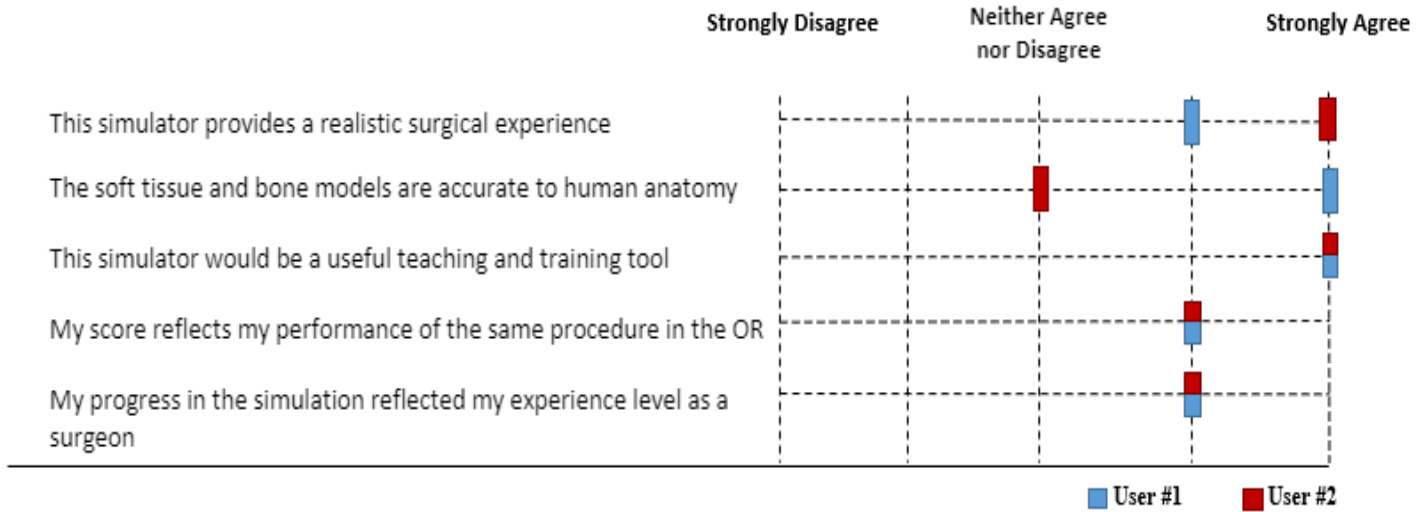
3. RESULTS AND DISCUSSION

Figure 8: User response to simulator validity questionnaire

The generated models were triangulated and refined versions of the high polygon segments, accurately resembling the patient's anatomy and successfully integrated into the VR system. Two experienced urological surgeons used the simulator to perform a nephrolithotomy on the patient generated from our workflow. Once surgeons had completed the procedure, they responded to a series of questions based on a 5-point Likert scale ranging from strongly disagree to strongly agree (Figure 6). The surgeons rated that the simulator was a level 3 and above in visual realism and accuracy for face validity, and level 4 and above for training usability, identification of surgical experience and reflection of operating room performance, thus demonstrating its content, construct, and criterion validity, respectively.

Additional comments by the surgeons indicated that haptic feedback of the final puncture to the duct could be increased and that the simulator could have potential in clinical application. A future clinical goal is to provide physicians with the opportunity to practice in VR on their actual patients' anatomy in preparation for real operations.

4. NEW OR BREATHROUGH WORK TO BE PRESENTED

The workflow to generate 3D soft tissue and bone models from CT scans to create a functional VR patient was developed using open source and modelling platforms. Models designed from this workflow were integrated into a nephrolithotomy VR system and surgeons were able to perform the procedure, confirming its face, content, construct, and criterion validity.

5. CONCLUSION

The successful integration of the models into Marion Surgical's PCNL system and the results of the validity questionnaire demonstrated the creation of an effective workflow to produce 3D models for use in a VR simulator for training nephrolithotomy. The models were efficient for haptic simulation while maintaining sufficient anatomical details and accuracy.

6. ACKNOWLEDGMENTS

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