Educational Material for 3D Visualization of Spine Procedures: Methods for Creation and Dissemination

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Abstract Spine anatomy can be difficult to master and is essential for performing spine procedures. We sought to utilize the rapidly expanding field of 3D technology to create freely available, interactive educational materials for spine procedures. Our secondary goal was to convey lessons learned about 3D modeling and printing. This project involved two parallel processes: the creation of 3D-printed physical models and interactive digital models. We segmented illustrative CT studies of the lumbar and cervical spine to create 3D models and then printed them using a consumer 3D printer and a professional 3D printing service. We also included downloadable versions of the models in an interactive eBook and platform-independent web viewer. We then provided these educational materials to residents with a pretest and posttest to assess efficacy. The “Spine Procedures in 3D” eBook has been downloaded 71 times as of October 5, 2016. All models used in the book are available for download and printing. Regarding test results, the mean exam score improved from 70 to 86%, with the most dramatic improvement seen in the least experienced trainees. Participants reported increased confidence in performing lumbar punctures after exposure to the material. We demonstrate the value of 3D models, both digital and printed, in learning spine procedures. Moreover, 3D printing and modeling is a rapidly expanding field with a large potential role for radiologists. We have detailed our

process for creating and sharing 3D educational materials in the hopes of motivating and enabling similar projects.

Keywords 3D printing · Additive manufacturing · Lumbar puncture · Spine procedures · Education

Abbreviations

ABS Acrylonitrile butadiene styrene
CAD Computer-aided design
PLA PolyLactic acid
STL StereoLithography

Background

Thorough understanding of spine anatomy is essential not only for diagnostic interpretation but also safe and effective performance of spine procedures. Moreover, visualizing spine anatomy in three dimensions is essential, allowing one to recognize and interpret overlapping structures on fluoroscopy. Existing educational material on spine procedures contains excellent illustrations, many utilizing 3-dimensional (3D) models. Additionally, there are numerous videos online demonstrating various spine procedures using 3D animations and actual patients. Meanwhile, newer technologies exist to share digital models via an interactive interface. Specifically, the iBooks platform by Apple and the website Sketchfab are freely available.

Interactivity, it is not limited to the digital realm. 3D printing, also referred to as “additive manufacturing” or “rapid prototyping,” is a technology which has been around for several decades and is rapidly gaining popularity. Broadly, a “3D printer” is any device that can turn a 3D digital model into a

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tangible object. Within medicine, 3D printing is rapidly gaining new applications including physician and patient education, surgical planning, surgical guides, and custom titanium implants [1–4]. In the future, printing of actual biologic structures such as a pancreas or liver has the potential to be revolutionary [5].

We sought to create interactive 3D educational resources on spine procedures. These included annotated 3D models in Apple iBooks and Sketchfab, physically printed models, and freely downloadable models that could be printed elsewhere. To illustrate the flexibility of our technique, we created models of a degenerative lumbar spine and lumbar arteries as well. We then sought to subjectively and objectively evaluate these materials with residents. This project also served as the impetus for formation of a 3D imaging lab, and our secondary goal was to convey lessons learned through this process.

Methods

There are two key elements to a 3D imaging and printing lab: Software to create the models and a printer to print them. For software, we purchased Mimics (Materialize, Leuven, Belgium). This software converts medical images to 3D models through the process of segmentation. 3D models are then optimized using 3Matic, the computer-aided design (CAD) counterpart to Mimics.

We purchased an Ultimaker 2 (Ultimaker, Geldermalsen, Netherlands) 3D printer based on positive consumer reviews for reliability and support. The Ultimaker 2 is a fused deposition modeling (FDM) printer, the most common type of consumer-level printer. Essentially, an FDM printer pushes plastic through a heated tip/extruder and deposits it layer-by-layer to build a model. The Ultimaker 2, as with most consumer printers, has a “single extruder,” which means it can only print one color at a time. The cost of the printer was approximately USD \$2500. Material for the printer is purchased as spools of filament costing approximately \$60 per 0.75 kg spool. For context, a lumbar vertebra requires about 20 g or \$1.62 of material. Currently, with an Ultimaker 2, there are two primary filament choices which are similar in price. PolyLactic Acid (PLA) is a non-toxic cornstarch-based plastic. Acrylonitrile butadiene styrene (ABS) is an oil-based plastic similar to that used in Legos.

We then created digital lumbar and cervical models. For the first lumbar model, we segmented a CT lumbar myelogram performed on a young patient. Details of the segmenting process are elaborated in a screencast at bit.ly/3ddicom. To summarize, segmentation begins with thresholding, which essentially says “select every pixel between x and y Hounsfield units.” Thresholding takes seconds and works very well for high-contrast objects such as bones and opacified vessels. However, segmentation becomes more

time-consuming when two objects of interest contact each other, as was the case with the bones and thecal sac on our myelogram. Manual separation of these two structures required several hours. We then exported the segmented model to CAD software for optimization. Optimization included fixing bad components of the model, smoothing, and filling in holes. Lastly, we reduced the number of polygons comprising the model and thus the filesize. Reduction was essential for compatibility with our interactive digital choices. The entire optimization process required approximately 10 min. As these models were intended for educational purposes, segmentation accuracy was not evaluated.

We then created models of a degenerative lumbar spine (Fig. 1) and the lumbar arteries. The challenge in creating the degenerative lumbar spine model was filling in large holes caused by osteopenia, which required some manual segmentation. The challenge with modeling the lumbar arteries was separating them from the adjacent osseous structures, similar to the lumbar myelogram.

Creation of the cervical model was similar but more complicated. We wanted to visualize both the vertebral arteries and the thecal sac structures not typically well-opacified on the same study. For the cervical model, we chose a young patient who received both a CT cervical myelogram and a CT angiogram. Utilizing both studies, we segmented the vertebrae, vertebral arteries, thecal sac, and cervical cord. These structures were then combined in 3Matic. Given that these studies were performed at different times, there was concern that patient flexion would be different and the structures would not “fit” together. Luckily in our case, patient position was similar between studies.

We then printed the lumbar and cervical models. For the lumbar model, we wanted to print the bones in white and nerves and thecal sac in yellow, which presented a challenge to our single-color printer. So, we used CAD software to design a model that could snap together: the thecal sac would

Fig. 1 Lumbar puncture simulated on a degenerative lumbar spine

snap onto the vertebral bodies, and the vertebral bodies would snap onto the posterior elements (Fig. 2). Details of this process are beyond the scope of the paper, but our screencast at bit.ly/3ddicom elaborates every step. Printing two vertebral bodies required approximately 6 h and printing the thecal sac approximately 2 h. Complicating the process was numerous print failures manifesting as printer “jams” where the filament stopped feeding forward. This is a well-recognized issue with current FDM printers. Given the limitations of a single extruder and print failures, we utilized a third party service with commercial printers (Whiteclouds, Ogden, Utah) to produce the full lumbar and cervical models as multicolor nylon powder prints (Fig. 3).

Next, we created an iBook (Apple Inc., Cupertino, California) utilizing the digital and printed 3D models and containing chapters on lumbar anatomy and lumbar punctures. The lumbar models (myelogram, degenerative, and angiogram) were converted to a format compatible with iBooks using Sketchup (Trimble Navigation, Sunnyvale, California) and included in the book. The process for creating a model compatible with iBooks is detailed at bit.ly/3dibook. The iBook is freely available on the iTunes bookstore and is titled “Lumbar Punctures in 3D.”

With the completion of these educational materials, we created a 16 question multiple choice pretest and posttest covering the content in the “Lumbar Punctures in 3D” book. The quiz was created with the Watu Pro (Kiboko Labs, Svoge, Bulgaria) Wordpress plugin and can be taken at fundamentalradiology.com. The questions emphasized anatomic concepts relevant to performing lumbar punctures. We also created a 12 question survey to ask readers about their experience. This included a question about their confidence

Fig. 3 Full-color nylon prints of the cervical (*left*) and lumbar (*right*) spine. Printing by Whiteclouds, Ogden, Utah

performing lumbar punctures reported on a Likert scale ranging from 0 (not confident at all) to 4 (very confident).

Next, we presented the educational materials at a radiology resident conference. The residents first took the pretest, then downloaded and reviewed the “Lumbar Punctures in 3D” book, then took the posttest and survey. The printed models were also made available at this conference.

We then created and published a more comprehensive book titled “Spine Procedures in 3D.” This covered additional spine procedures including cervical and lumbar interlaminar and transforaminal epidural steroid injections and facet injections. Finally, all spine procedure models were uploaded to SketchFab (bit.ly/spinemodels) as a platform-independent means for interacting with and downloading our models.

Results

Our goal of providing free interactive models of spine procedures resulted in a free iBook, several printed models, downloadable StereoLithography (STL) versions of our lumbar and cervical models, and a website relating our experience with several instructional videos. As of October 5, 2016, the “Lumbar Punctures in 3D” and “Spine Procedures in 3D” books have been downloaded 71 times.

Fourteen residents and two fourth year medical students took the pretest. Thirteen residents and two fourth year medical students took the posttest. Results of the pre- and posttest are summarized in Table 1. Overall mean pretest score was 70%, which improved to 86% on the posttest. The two fourth year medical students showed the most improvement (34 to 56%). The three fourth year radiology residents showed the least improvement (86 to 92%). The fourth year radiology residents had all performed >20 lumbar punctures previously

Fig. 2 Two lumbar vertebral levels and thecal sac modeled to snap together. The *black arrows* indicating the direction of assembly for the anterior and posterior elements. The thecal sac snapped onto the posterior elements (holes not shown)

Table 1 Results of pretest and posttest grouped by postgraduate training level

	Pretest average score	Pretest # of respondents	Posttest average score	Posttest # of respondents
Overall	70%	16	86%	15
PGY-0*	34%	2	56%	2
PGY-1		0		0
PGY-2	71%	5	90%	5
PGY-3	67%	4	91%	4
PGY-4		0		0
PGY-5	86%	5	92%	4

*PGY-0 = medical student (2 fourth year medical students in this case)

on a fourth year elective. All other participants were less senior and had performed <5 previously. The questions showing the most dramatic improvement related to knowing the epidural space extend along the exiting nerve root (25% improved to 67%) and that the mid-pedicular line is a marker for the most lateral extent of the thecal sac (53% improved to 87%).

Participants were also surveyed regarding their confidence with performing lumbar punctures before and after the educational material (Fig. 4). Based on a Likert scale from 0 to 4, mean confidence increased from 1.5 before the educational material (between “Not that confident” and “Somewhat confident”) to 2.2 (between “Somewhat confident” and “Confident”) after the educational material.

Participants were also surveyed regarding the helpfulness of the provided educational materials (Fig. 5). For all materials and the experience overall, helpfulness was gauged as between “Helpful” and “Very helpful.”

Finally, participants provided open-ended feedback about the book. Two people commented that printing the models did not seem to be necessary for understanding. Another wanted more coverage of determining interlaminar space levels on fluoroscopy. Two others wanted more information on

Fig. 4 Confidence performing lumbar punctures before and after exposure to educational material. (0 = not confident at all, 1 = not that confident, 2 = somewhat confident, 3 = confident, 4 = very confident)

troubleshooting other complicating factors such as obese, postoperative, or altered patients.

Discussion

This project spurred the formation of a 3D imaging lab and taught the participants numerous lessons in the emerging modalities of 3D visualization and printing. Our primary intent is to share both the materials created with this project and the lessons learned. To that end, the screencasts listed above provide detailed walkthroughs that enable anyone to create, optimize, and design on their own 3D model in a manner similar to ours.

There are significant but not insurmountable challenges to starting a 3D imaging lab. There is a cost associated with proprietary software and a 3D printer. However, free software alternatives such as Slicer are also available. Moreover, owning a printer enhances understanding of the process but is not necessary. Most communities will have numerous printing options including commercial printing services, public libraries and university departments, and other hospitals. Perhaps, the largest challenge is a technical one. Radiology training does not prepare one for this process, and current segmentation and CAD software can be difficult to master. Future improvements in software usability and outside consulting services are potential methods for lowering this hurdle.

As a relatively new technology, there are significant technical challenges to 3D printing. First, segmentation is a very time-consuming process. As algorithms for automated segmentation continue to improve, this should reduce segmentation time. Second, while optimizing a 3D model for printing is relatively straightforward, utilizing CAD software to actually design on and modify a model is quite challenging. Finally, consumer 3D printers still have a high print failure rate and limited options for printing in multiple colors and materials.

Regarding our educational materials, both residents and medical students improved their performance on the posttest after exposure. Not surprisingly, those with the least prior experience showed the most improvement. Also, the most dramatic improvement was seen in two questions testing anatomic knowledge more useful for transforaminal epidural steroid injections, procedures not typically performed by residents. This likely accounts for the poor pretest performance. The educational materials helped modestly with confidence in performing lumbar punctures. However, mean confidence still remained near the “Somewhat confident” mark as opposed to “Very confident.” Clearly, hands-on experience performing lumbar punctures on actual patients is the gold standard for becoming proficient. We hope to implement this 3D interactive iBook in standard resident training with incorporation of actual patient lumbar puncture procedures as a part of the posttest. Another future direction includes creation of a

Fig. 5 Helpfulness of different educational materials by number of respondents

lumbar puncture training model. While models are readily available for purchase, 3D printing would allow for creation of models simulating variants such as severe degenerative disease and postoperative spines. The strength of 3D modeling and printing is not in mass production, rather the rapid creation of models demonstrating variant anatomy.

Participants found all the educational materials “Helpful” to “Very helpful” overall. Notably, there was no reported difference between printed models, interactive models, and still pictures of 3D models.

Two participants did not think printing the models was necessary. Thus far, 3D printing has taken hold the most with surgeons for pre-operative planning and this trend will continue. Radiologists tend to think in axial slices and may not find 3D models and prints as necessary. However, as a service industry, it is reasonable for radiologists to be aware of this evolving useful technology and potential growth area.

Results of our educational materials have some limitations. A simple pre- and posttest around an intervention is almost guaranteed to show an improvement. Testing over time to evaluate retention would make our results more meaningful. Regarding survey results, there was likely a bias towards positive responses given this was our home institution. Additionally, there were no questions asking for a direct comparison between different educational materials. However, we suspect that in the setting of understanding lumbar spine anatomy, all three educational materials are truly complementary and equally helpful.

Conclusion

We have conveyed our experience starting a 3D imaging lab and demonstrated that 3D models have educational value for instructing trainees on lumbar punctures. We have also highlighted that 3D printing is particularly useful for modeling patient-specific anatomy such as degenerative disease. 3D printing is becoming increasingly popular, and we hope to encourage radiologist involvement by detailing our methods for creating and printing useful 3D models.

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