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Facilitating surgeon understanding of complex anatomy using a three-dimensional printed model

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ABSTRACT

Background: 3-dimensional prints (3DP) anecdotally facilitate surgeon understanding of anatomy and decision-making. However, the actual benefit to surgeons or patients has not been quantified. This study investigates how surgeon understanding of complex anatomy is altered by a 3DP compared to computed tomography (CT) scan or CT + digital reconstruction (CT + DR).
Materials and methods: Key anatomic features were segmented from a CT-abdomen/pelvis of pygopagus twins to build a DR and printed in color on a 3D printer. Pediatric surgery trainees and attendings ($n = 21$) were tested regarding anatomy identification and their understanding of point-to-point distances, scale, and shape.
Results: There was no difference between media regarding point-to-point distances. The 3DP led to an increased number of correct answers for questions of scale and shape compared to CT ($P < 0.05$). CT + DR performance was intermediate but not statistically different from 3DP or CT. Identification of anatomy was inconsistent between media; however, answers were significantly closer to correct when using the 3DP. Participants completed the test faster with the 3DP (6.6 ± 0.5 min) ($P < 0.05$) than with CT (18.9 ± 2.5 min) or CT + 3DR (14.9 ± 1.5 min).
Conclusions: Although point-to-point measurements were not different, 3DP increased the understanding of shape, scale, and anatomy. It enabled understanding significantly faster than other media. In difficult surgical cases with complex anatomy and a need for efficient multidisciplinary coordination, 3D printed models should be considered for surgical planning.

Introduction

We recently separated pygopagus conjoined twins joined at the buttocks, who had fused spinal cords, imperforate anus without fistula, and a single anal sphincter complex. Conjoined twinning is rare and presents unique surgical challenges. Each connection is unique with highly variable and complex anatomy. It is the complexity of this connection that dictates the possibility of separation. Therefore, a comprehensive examination and radiologic workup is required to characterize the connection.[1,2] Using conventional imaging techniques, elucidating the details of any connection can be tedious and time consuming.

We employed the use of 3-dimensional printing (3DP) technology to model the twin's complex anatomy to assist the

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large multidisciplinary team in preoperative planning sessions. As reported in other preoperative uses, the involved surgeons felt that the 3DP was helpful for understanding the anatomy beyond what the conventional imaging provided, particularly regarding 3D spatial relationships between structures.[3-12] Although the surgeons regarded the 3DP as helpful, it remained unclear how and to what extent the 3DP quantitatively facilitated understanding of the anatomy.

Our goal was to determine the specific benefits a 3DP model offered surgeons in preoperative planning. To do so, we tested the ability of pediatric surgeons to identify anatomy and understand point-to-point measurements, shape, and scale in pygopagus twins using conventional two-dimensional (2D) imaging (computed tomography [CT]) *versus* CT with digital reconstructions (CT + DR) *versus* the 3DP. We hypothesized that the 3DP would offer greater accuracy at understanding length, shape, scale, and identification of anatomy.

Material and methods

CT scanning, digital modeling, and 3D printing

To elucidate the anatomy, pygopagus-conjoined twins underwent a CT of the abdomen and pelvis (Aquilion One 320, Toshiba Corp, Tustin, CA). To improve imaging of the GI and GU tracts, a single "triple" contrast study was done. Imaging was performed 10 min after an intravenous contrast bolus of 0.25 mg/kg optiray 320 was given to each twin, followed by 0.25 mg/kg optiray 320 given to acquire the arterial phase during the scan. Additional dilute water soluble iodinated enteric contrast was instilled antegrade with gravity into the distal limb of each twin's colostomy to distend the distal colon and rectum. The patients were imaged using a weight-based CT dose technique (kvp 100, MA 125 rotation time 500 ms) from the epigastrium to the proximal femurs. The CT volume was reconstructed to 0.625 mm contiguous slices in standard orthogonal planes prescribed to the unique anatomy of the patients. The anatomy of the skeleton, renal and urinary tract, distal colon and rectum, and thecal sac were then segmented from the CT data into 3D surface meshes using Mimics V17.0 software (Materialize, Leuven, Belgium) to create a DR (Fig. 1A). Because specific structures were segmented without the surrounding supporting soft tissues, anchoring and support structures to keep unconnected anatomic features correctly positioned were added using Autodesk Maya V12 software (Autodesk, San Rafael, CA). A scale-accurate 3DP was then printed using a Z-corp, Z-print Z650 (Z-corp, Burlington, MA) powder bed and ink-jet printer (Fig. 1B).

Examination development and testing

To determine how the 3DP benefited surgeon understanding of pygopagus anatomy, a fifteen-question examination was developed that tested four general areas: understanding of linear point-to-point distances, scale, shape, and identification of anatomy (Table). These areas were chosen based on discussions with the surgeons who used the model in preoperative planning and relayed that the model seemed most helpful in these realms. Each question was formulated to fall within each of these four realms. We restricted the possible questions to those that were answerable using any of the three mediums, and which fell within the reasonable domain of knowledge of our available cohort of study participants. Finally, because our intent was to focus the study on the accuracy and rate of knowledge acquisition from the different modalities, we avoided questions in which feature identification could reasonably be expected to be subjective. The first seven questions asked examinees to determine the distance between anatomic landmarks, on both soft and bony tissues. Some spans fell within an individual twin while others were between both twins, requiring the examinee to orient themselves to both patients. The spans tested were also chosen because they were between specific and distinct points that could be easily identified on all three media. Q8 and Q9 tested the surgeon's sense of scale. The DR of the right kidney of twin A and the right femur of twin B were reproduced as 3D prints at full scale, and at four additional scales with 10% linear difference between each (Fig. 2A, B). Examinees were asked to select which of the models was true to the patient's size. These two structures were chosen because of their well-defined profile, making them easy to identify on all media and amenable to reproduction by 3D printing. Q10 and Q11 tested the surgeon's sense of shape and contour. Each twin

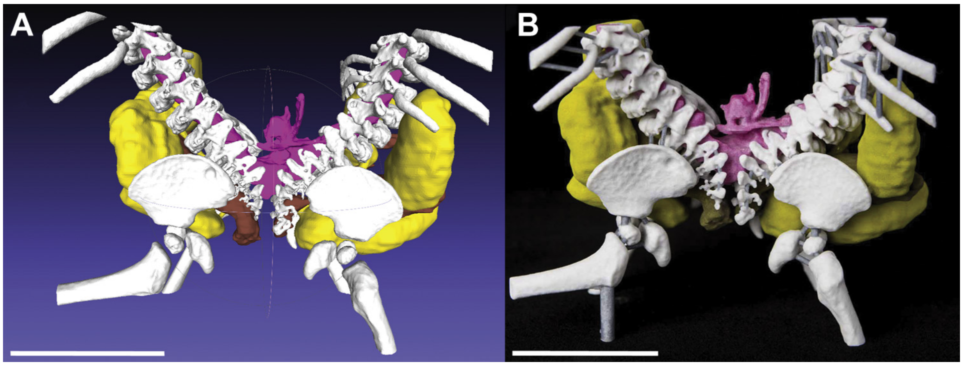

Fig. 1 – Digital reconstruction (A) and 3D print (B) of pygopagus conjoined twin anatomy. White, bone; yellow, kidneys and collecting system; brown, colon and rectum; and magenta, spinal cords and thecal sac. Scale bar = 5 cm.