Advances in 3D printing have resulted in increased availability and expanded medical applications. Anatomically accurate 3D printed models have a demonstrated role in education and resident training. Patient-specific models are valuable for patient education regarding the specific pathology and planned surgical procedure. The ability to combine multiple materials within a 3D printed model allows for re-creation of the pathological entity and affords the opportunity to simulate and compare surgical approaches. We present the utility of a multimaterial 3D printed model for the surgical planning in a case of complex deformity of the skull base and craniovertebral junction.

Case Presentation

An 11-year-old boy with multiple congenital abnormalities, who had undergone a previous suboccipital decompression and C-1 laminectomy with an occipital-C2 instrumentation and fusion at the age of 5 years, presented with progressive cervical myelopathy. MRI (Fig. 1A and B) and CT imaging demonstrated significant platybasia with progressive basilar invagination, resulting in ventral compression of the cervicomedullary junction. Additionally, the left C-2 screw appeared to no longer be located within the bone, and the right C-2 screw demonstrated haloing suggestive of loosening. Due to the ventral bony compression, there was consideration for a possible anterior versus lateral approach for removal of the dens and anterior arch of C-1 followed by posterior revision of hardware. Given the presence of multiple skull base defects and tortuous vascular anatomy, a 3D model for surgical planning was fabricated (Fig. 1C and D).

Method

Dual-energy CT source data were acquired at 90 and 150 kV using a Somatom Force scanner (Siemens Healthcare). Using syngo.via software (Siemens Healthcare), 2 data sets were selected (virtual noncontrast with iodine removed, series with bone and metal subtracted out). DICOM data were imported into the Intellispace Portal (version 6.0.3, Philips Healthcare) and segmented into 3 individual 3D volumes (bone and metal using noncontrast series, vessels using subtracted series). These tissues were then saved using STL (standard tessellation language) format. STL files were subsequently printed combining 3 different materials (VeroWhite, VeroMagenta, and VeroBlack) on a 3D printing device (Objet260 Dental Selection, Stratasys Ltd.). The printing process involves creation of ultrathin layers of photopolymer resins, which are applied in liquid form. Exposure to ultraviolet light results in a rapid hardening of the liquid layers. The model is printed along with water-soluble support material, which is then

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The utility of a multimaterial 3D printed model for surgical planning of complex deformity of the skull base and craniovertebral junction

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Utilizing advanced 3D printing techniques, a multimaterial model was created for the surgical planning of a complex deformity of the skull base and craniovertebral junction. The model contained bone anatomy as well as vasculature and the previously placed occipital cervical instrumentation. Careful evaluation allowed for a unique preoperative perspective of the craniovertebral deformity and instrumentation options. This patient-specific model was invaluable in choosing the most effective approach and correction strategy, which was not readily apparent from standard 2D imaging. Advanced 3D multimaterial printing provides a cost-effective method of presurgical planning, which can also be used for both patient and resident education.

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removed after printing with powerwashing. The cost of the print material was US $270, and it took 13 hours to print. Preoperative and postoperative models were created for direct comparison.

Surgical Planning

After reviewing the multimaterial 3D model, several key concepts became apparent. 1) An anterior approach would be significantly challenging as the rotation of the upper cervical spine is such that the dominant left vertebral artery is located within the midline. Additionally, bilateral defects in the inferior aspect of the petrous temporal bone result in fully exposed carotid arteries (Fig. 2). 2) A lateral approach would require a transpetrosal approach because the top of C-1 and the tip of the dens are impacted beneath a remodeled petrous apex on the right. This would necessitate sacrifice of hearing on the right. Additionally, the tortuous path of the right vertebral artery would require complete anterior transposition of the vessel (Fig. 1C and D). 3) A posterior approach would have a limited working corridor due to settling and hyperlordotic cervical spine. Removal of the already placed occiput–C2 instrumentation would be a challenge due to the limited angle of approach. 4) The true pathology was not the settling of C-1 and C-2 into the brainstem as most of the compression is secondary to the platybasia and the tip of the clivus. Rather, the problem is the anterior translation of the spinal canal as the settling has occurred, resulting in further draping of the brainstem over the clivus. 5) Our solution was not to remove the clivus and ventral C-1 and C-2 elements but to decompress the cervical spine and translate it posteriorly while distracting at the craniocervical junction. Traction alone would not achieve an adequate decompression of the ventral brainstem. 6) There were no viable fixation options at C-2 due to the previously loosened hardware on the right and the dominant high-riding vertebral artery on the left. Additionally, no true C-3 lateral mass was available; it is conjoined to C-2. The C-4 and C-5 lateral masses on the right side were thinned due to impression from the head of the C-2 screw and not thick enough to accommodate the smallest lateral mass screw. To achieve reliable fixation, the construct would have to be extended to T-1 or T-2.

Based on the 3D model, we decided to address the problem through a posterior approach with a plan to decompress the subaxial cervical spine and then concurrently distract and posteriorly translate the cervical spine in relation to the occiput.

Procedure

At the time of surgery the model was placed on a stand next to the surgical field for reference during the case. The patient was placed in a halo ring for a planned postsurgical halo vest. Once the patient was prone, we attempted to distract the craniocervical junction under fluoroscopic guidance and with neuromonitoring, with no significant motion noted. As predicted, our working corridor was limited by the degree of settling, the hyperlordotic cervical spine, and the hyperkyphotic thoracic spine (Fig. 3). However, due to loosening of the right C-2 screw and the left C-2 screw no longer being in bone, both were removed with the rod attached and did not require a driver being placed within the screw head.
A laminectomy was performed from the remaining C-2 to T-1, after which there was significant posterior translation of the spinal cord. In concordance with the model, fixation was achieved on the left side from C-4 to T-2 and on the right side from C-6 to T-2. Throughout the opening and fixation, the model was consulted to confirm different anatomical landmarks. Once the hardware had been placed and the rods contoured, the subaxial spine was locked into the rod, with the occipital portion free to move. Heavy rod holders were placed on the subaxial rods, and the Mayfield headholder was loosened. Under fluoroscopic guidance, the subaxial spine was translated posteriorly while the occiput was distracted and then locked into position (Fig. 4). On postoperative MRI the improved position of the brainstem in relation to the clivus was demonstrated with decreased ventral compression (Fig. 5A and B). For a direct comparison with the preoperative model, a postoperative model was fabricated which confirmed this improved spinal alignment and reduction of the C1–2 complex from the foramen magnum (Fig. 5C and D).

Discussion

The use of patient-specific computer-aided rapid prototyping has been previously used for surgical planning in complex spine procedures.3,10,11 In these settings, the models created were of a single material reflecting only at the osseous anatomy. They demonstrated the utility of being able to plan corrective osteotomies and pedicle screw fixation as well as an intraoperative reference. In the field of neurovascular surgery, single-material rapid prototypes have been used for open surgical planning and as templates for endovascular treatment.1,5,9 Skull base models with patient-specific pathology have been produced with multiple materials for training simulation purposes.5,6

Our technique is unique in its utilization of advanced 3D printing techniques to develop a model of a complex craniovertebral junction deformity with abnormal vascular anatomy and previously placed instrumentation. This unique combination of technology and pathology allowed for comprehensive surgical planning beyond that achieved with standard imaging. When this case was presented at a multidisciplinary skull base conference attended by neurosurgeons, neurotologists, and head and neck surgeons, multiple opinions regarding the optimal surgical approach...
were suggested. All surgical treatment options concentrated on various methods of removing the ventral pathology based on the MRI/CT imaging findings. A major limitation of planning from standard imaging was the inability to clearly visualize the craniocervical junction due to coronal and sagittal plane deformity. As such, it was impossible to obtain in-plane views of the areas of interest. The best visualized region of pathology appeared to be the ventral brainstem compression. Even with the 3D file from which the model was constructed, it was difficult to look down the plane of the spinal canal. It was not until the 3D model was reviewed that it became clear that the key maneuver involved not only distraction but posterior translation of the cervical spine as well as cervical decompression to allow for less kinking of the brainstem over the clivus. Additionally, the model was an invaluable intraoperative resource, which contributed to the success of case.

The current state of 3D printing does not lend itself to the creation of a complex model on a routine basis. However, as technology improves and multimaterial 3D printers become more accessible, it has the potential to become an increasingly important part of case preparation. Also, in the era of work-hour restrictions, these models may be an important training adjunct for neurosurgical residents. Additionally, patient-specific models can serve as a useful tool for patient education.

One limitation of the current generation of modeling is the static representation generated; that is, there is no flexibility of modeled ligaments, vessels, and other soft-tissue structures. Ideally, differential tissue densities, compressibility, and elasticity could be generated, allowing realistic predictions of the forces required for deformity correction, or the limits of transposability of vessels or neural structures.

Conclusions

Multimaterial 3D printing is an effective preoperative tool for evaluating complex skull base pathology. Patient-specific modeling allows for improved resident and patient education.

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References


Disclosures

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