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3D Printed Titanium Prosthetic Reconstruction of the C2 Vertebra: techniques and outcomes of 3 consecutive cases.

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The device(s)/drug(s) that is/are the subject of this manuscript is/are exempt from FDA or corresponding national regulations because it is a unique custom patient-specific device. No funds were received in support of this work.

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Abstract:

Study Design:

3 patients were treated at our centre with patient-specific 3D-printed titanium prostheses for the reconstruction of structurally compromised C2 vertebrae

Objective:

To describe our surgical and device design approach to these clinical scenarios and evaluate their outcomes

Summary of Background Data:

There are a limited but increasing number of case reports and series describing the use of 3D printed prostheses for high cervical surgery.

Methods:

We have collated and reviewed three cases using patient-specific 3D printed prostheses.

Results:

We report two cases arising from neoplastic destruction; one resulting from metastatic medullary thyroid carcinoma, and the other from multiple myeloma. We additionally describe a case of C2 compromise as a complication of rheumatoid arthritis. All patients included in this report achieved successful surgical outcomes and symptom relief without significant complication. Clinical and radiological follow up has demonstrated good outcomes in all cases up to 14-months post-procedure.

Conclusions:

These cases describe successful use of custom 3D-printed prostheses for reconstruction of the anterior vertebral column through C2, and add to the emerging body of literature detailing the use of custom prostheses for complex spinal surgery.

Key Points:

1. To describe and evaluate the use of patient-specific 3D printed prostheses for challenging destructive pathologies of the C2 vertebra.

2. To describe how 3D printed prostheses can re-instate structural integrity to the anterior spinal column while preserving atlanto-occipital mobility.

3. To report a case utilising a 3D printed prosthesis for rheumatoid destruction of the C2 segment, which is in our understanding the first described use of such a prosthesis for this application.

4. To demonstrate the pathway from clinical problem to design, digital rendering and 3D printing in order to provide a patient-specific custom prosthesis.

Key words: 3D printing, neurosurgery, implant, prosthesis, cervical, axis, rheumatoid, patient, specific, spinal, metastatic, oncological, surgery

Level of Evidence: 4

Introduction:

Structural compromise of the C2 vertebral body can occur as a result of a number of pathological processes, including traumatic, degenerative, neoplastic, and inflammatory.[16] Degenerative and traumatic pathologies are well catered for by bulk-manufactured cervical prostheses below C2, [18, 20] however no commercially available device can address deficiencies of C2 or its articulation with C1. Addressing the resultant axial instability, or potential instability, is an important consideration of treatment of the C1-C2 segment. Theoretically, reconstruction of the anterior column is the most effective strategy. Comprehensive posterior fixation options are readily available, but such options do not directly address axial forces in scenarios of C2 vertebral body compromise. The emergence of 3D printing as a manufacturing technique for custom implants, first explored by D'Urso et al. in 1999, [4] and now realised in the production of custom prostheses, [12, 22] has opened up new and unique possibilities for restoring the anterior column of C2 and below. The three cases presented in this report describe two cases of neoplastic destruction of the C2 vertebral body, and one of inflammatory osteolysis, utilising custom titanium prostheses to reconstruct the anterior column of C2.

Patient 1

History

A 56-year-old female with a known history of medullary carcinoma of the thyroid was referred to our clinic. The malignancy had been diagnosed ten years previously and treated with primary surgical resection and post-operative radiotherapy. Six years later the patient was diagnosed, on surveillance imaging, with two metastatic lesions of the right lung and underwent resection via thoracotomy. A further two years later another lung lesion was identified and subsequently resected. Six months prior to presentation to our clinic a PET scan was reported as showing no evidence of active metastatic disease. The patient presented to our clinic with new onset neck pain and new imaging features consistent with a lytic metastatic lesion of the body of the C2 vertebra. The patient was neurologically intact and exhibited a reasonable range of neck movement.

Preoperative workup and planning

It was initially determined that the tumour could not be completely resected, and that the mainstay of oncological treatment would be radiotherapy. Reconstructive surgery was proposed because of concerns regarding potential axial instability and C2 collapse due to lytic destruction. Primary radiotherapy was considered and decided against because of the potential risk of axial instability consequent upon a reduction in tumour mass. It was anticipated that the significant consequences of C2 vertebral collapse could potentially be prevented via elective pre-radiotherapy C2 body reconstruction utilising 3D printed technology (additive manufacturing), with no commercially available prosthesis able to provide the necessary support and stability. A custom interbody implant was subsequently designed, incorporating fixation to the lateral masses of C1, support of the anterior arch of C1, and distal axial column support to the upper endplate of C3 with transosseous fixation through the body of C3. The design was then incorporated into a 3D digital rendering of the C1-C4 vertebral segment, with virtual resection of the tumour and custom tailoring of the device to the patient's anatomy and virtual surgical defect. The finalised digitally rendered 3D prosthesis was manufactured from Titanium Alloy (Grade 5) using the Arcam A1 Electron Beam Melting device (Anatomics Pty. Ltd. in association with CSIRO, Melbourne, Australia). The surfaces were finished with an "as printed" rough finish on bone facing surfaces, and a matte finish on soft tissue adjacent surfaces. High-shine polished surfacing was used for screw fixation holes. The fixation holes were countersunk on pre-planned vectors to accommodate off-the-shelf screw fixation.

Intraoperative and anaesthetic technique

The patient underwent a general anaesthetic. Nasal intubation was used to improve surgical access to the submandibular region. Exposure was achieved via an oblique anterior cervical approach. Tumour and bone resection was performed according to preoperative planning based on the 3D-printed model and radiological imaging. The information gleaned from the model was essential to optimise tumour and bone resection in order to optimally fit the prosthesis, and achieve the desired cytoreduction for adjuvant radiotherapy. The prosthesis was centrally packed with allograft and secured with transarticular and transosseous fixation (DePuy Synthes). The patient was then re-positioned prone, and the head fixed in position with the three-point Mayfield clamp. Posterior fixation from C1 to C3 was performed through a midline exposure to supplement the anterior column reconstruction. Posterior fixation was navigated and augmented with posterior allograft. No intraoperative complication relating to the anterior prosthesis and reconstruction was encountered. While it was initially intended that lateral mass fixation at C1 would be performed, this was modified to bilateral laminar fixation due to poor bone stock in the lateral masses.

Postoperative recovery

The patient experienced transient minor dysphagia and dysphonia which resolved by three weeks. The patient otherwise made an uneventful recovery from surgery. The patient was mobilised on day two post procedure in a firm cervical collar.

Follow up

At initial post-operative review, the patient remained in a firm cervical collar. The patient reported no significant neck pain and a marked reduction in analgesia use. Post-operative and review imaging has remained stable throughout. The patient subsequently underwent adjuvant oncological management with radiotherapy and chemotherapy. Her follow-up now extends to 14 months. She remains pain free, neurologically normal and has stable radiological follow up. Her metastatic disease has however progressed in other organ systems.

Patient 2

History

A 63-year-old male presented with a history of upper-cervical neck pain in the absence of neurological symptoms or signs. Imaging demonstrated a gross destructive process involving the body of C2 and the upper body of C3, as well as other scattered lesions throughout the axial skeleton. A clinical diagnosis of multiple myeloma was made and confirmed by bone marrow aspiration from the left iliac crest.

Preoperative workup and planning

Consideration was given to long-term collar stablisation, or alternatively occipitocervical fusion, however the lack of reconstruction to the anterior column was considered to be a significant disadvantage. From the patient's perspective it was desirable to maintain as much craniocervical mobility as possible. In light of our experience with Patient 1, the patient was offered C2/C3 vertebral body resection and reconstruction using a custom 3D printed titanium implant, manufactured by the same additive manufacturing technique described in our first case.

Intraoperative and anaesthetic technique

The patient underwent a trans-nasal intubation. The surgical exposure of C1 to C4 was by a right oblique anterior cervical exposure. Resection of C2 and C3 was performed according to preoperative planning based on the 3D printed model and radiological imaging. The 3D custom prosthesis was implanted and secured with cancellous screws to the C1 lateral masses bilaterally and to the C4 vertebral body. The patient was then repositioned into a prone position with the head secured with the three-point Mayfield clamp. A midline exposure of C1 to C4 was performed with navigated fixation with lateral mass screws from C1 to C4 and posterolateral grafting.

Postoperative recovery

The patient’s recovery required a short period of ventilator support to allow swelling of the nasopharynx and upper airway to resolve. Recovery was ultimately without neurological sequelae and post-operative imaging documented satisfactory placement of the anterior column device and posterior fixation. The patient subsequently proceeded to adjuvant oncological management.

Follow up

At 4 month review the patient was pain free and without any neurological dysfunction. He was subsequently weaned from his hard collar. Radiological follow-up has remained stable.

Patient 3

A 72-year-old man with a longstanding history of rheumatoid arthritis presented with severe upper cervical neck pain following a fall. Imaging demonstrated substantial lytic bone loss of the vertebral body of C2, without definite pathological fracture. After a full medical and rheumatological work up, the patient was offered C2 vertebral body excision and reconstruction. Device design and manufacture followed the same pathway as our prior two cases. The surgical procedure utilized the same technique, with anterior resection and prosthetic insertion being followed by navigated lateral mass fixation. Histological assessment of the extensive excised soft tissue mass filing the lytic defect and extending into the epidural plane confirmed pannus associated with his long-standing rheumatoid arthritis.

Follow-up

The patient is currently 6 months' post procedure. He has been weaned from his external orthosis, is neurologically intact and pain-free. Radiological follow has been stable.

Discussion

3D printing has been utilized in neurosurgery to treat patients with complex pathologies, and improve patient outcomes.[17] Examples include the production of custom cranioplastic plates,[2] the use of pathoanatomical models for the planning of intracranial surgical procedures,[7-9] and tailored geometry of implantable prostheses in reconstructive skull vault[10] and skull base surgery.[5] Models have also been utilized for surgical training.[1] 3D printing in spinal surgery was first reported in 1999, with the technology used to aid surgical planning.[4] In 2007, the use of a custom 3D printed drill template was reported for a posterior cervical surgery case, representing the first time that a 3D printed device had been used for intraoperative guidance.[13] In 2016 the first reported case of a 3D printed spinal implant was published.[15]

Reconstructive and internal fixation techniques for the atlantooccipital and atlantoaxial levels share a common disadvantage when compared with techniques for the subaxial spine, arising from difficulties in anterior column reconstruction. Current commonly used surgical techniques rely on posterior fixation and grafting, with fixation screws resisting axial, sagittal and rotational forces until fusion has occurred. Axial forces are suitably accounted for in the sub-axial spine with well-defined anterior column reconstruction technologies and techniques. Production prostheses for the axial spine are not viable commercially due to the relative scarcity of requirement, and significant patient variability in prosthesis geometry required. Bespoke 3D printing overcomes these issues, and provides suitable anatomical and biomechanical solutions for cervical axial spine reconstruction and fixation. In 2016 Phan et al. reported the first use of a 3D printed polymer prosthesis in the axial spine with a posterior C1/2 fixation device.[15] Xu et al. subsequently published the first reported use of a 3D printed device for anterior reconstruction of the axial spine in a 12-year-old patient with C2 Ewing's Sarcoma. [22] This was followed by Mobbs et al. in 2017, who reported reconstruction of the C1/2 segment with the fitting of an anterior prosthesis fixated to the skull base, supplemented with posterior fixation. [12]

Here we present the first series of three consecutive C2 anterior reconstructions with 3D printed patient-specific prostheses, and the first rheumatological application.[12, 15, 22] While our cases have so far only had short-term follow-up, all patients have done well clinically, with resolution of their presenting pain and radiologically stable appearance of their reconstructions. In regards to our surgical approach, we opted against an initial posterior approach (as outlined by Mobbs et al.),[12] instead opting to address tumour resection and cervical cord decompression as the first surgical priority, supplemented with posterior fixation. This method proved safe and effective, while permitting the maintenance of atlanto-occipital mobility.

On the basis of limited experience, it appears that this novel technique has utility in managing what can otherwise be highly challenging or in-operable surgical problems. There appear to be several advantages. Importantly, it permits aggressive tumour resection, with subsequent restoration of the anterior column and it's axial loading capacity in anticipation of subsequent oncological management. As oncological processes result in highly variable destruction of bone and alteration of cranio-cervical anatomy, custom implantable devices have unique utility in filling the bony defect after tumour resection. Additionally, the preoperative virtual modelling, on the basis of which the prostheses are customised, allows for planning of screw trajectory and length, thereby minimizing the risk of neurovascular complications and maximizing screw-bone interface. The benefits of 3D printed models for surgical planning of the complex cervical axial spine was well reported by Govsa et al. in their series of treating C1 fractures,[6] and by Chhabra et al. in their series of ten patients who underwent surgery for developmental cranio-vertebral junction anomalies.[3] The use of such models aids visualisation and planning, with the potential to reduce operating time and blood loss,[21] and improve the accuracy of device placement. Almost all customized prostheses to date have been made from titanium alloy, due to its biomechanical compatibility with trabecular bone structure.[14, 21] There is an increasing body of evidence supporting the notion that the porous nature of 3D printed titanium prostheses results in superior osseoconductivity and integration compared with polyetheretherketone (PEEK) and plasma sprayed porous titanium-coated PEEK devices.[11]

All cases to date utilising 3D printed patient-specific prostheses for spinal surgery have had only short-term follow up. This technology is uniquely suited to anatomically challenging cases, with 3D printed prostheses having the theoretical benefit of improved load distribution,[21] superior osseointegration,[11] reduced stress shielding, and possibly a decreased risk of subsidence.[7, 19, 22] Maintenance of mechanical integrity has been demonstrated at short term follow-up in all but one spinal surgery application, in which an asymptomatic mechanical failure of a sacral prostheses occurred.[19] It can only be speculated as to whether this failure was a design, materials or manufacturing issue, however it does highlight the potential role for dedicated design and manufacturing companies for custom 3D printed medical prostheses, who could combine an understanding of materials, surgery and biomechanics to work in association with surgeons to find optimum solutions to challenging clinical problems.

It will be interesting to observe how and when a regulatory framework for patient-specific 3D printed implants develops, and what shape this will take. Over time, barriers to the uptake of patient-specific 3D printed prostheses, namely cost, time to production, and restricted access to additive manufacturing technology will decrease, permitting wider access to this exciting and innovative technology.

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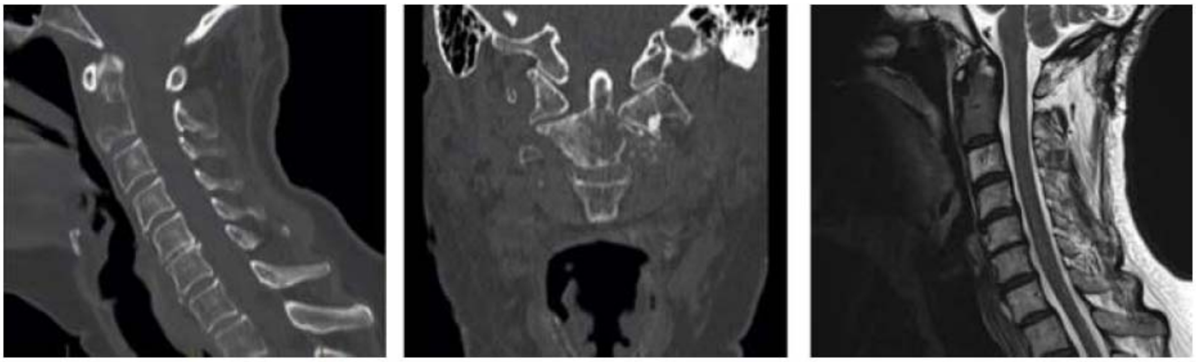
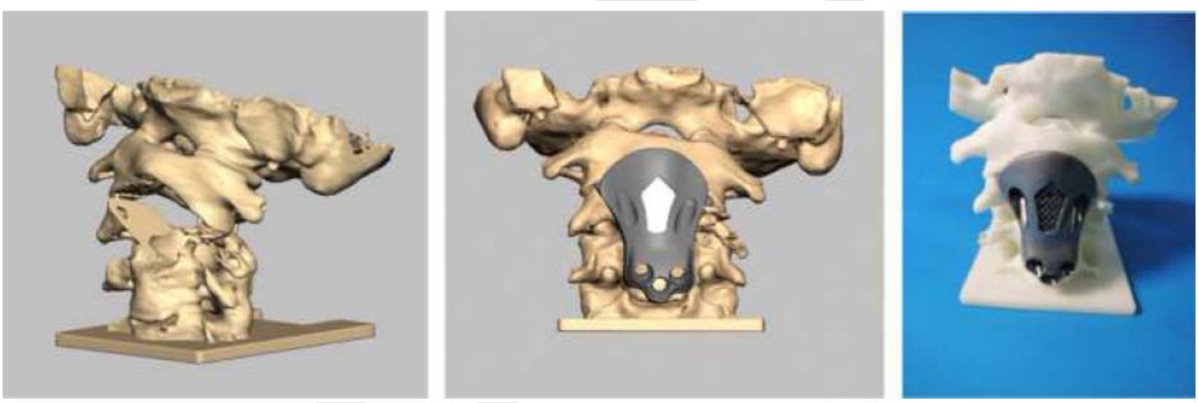


<u>Figure 1</u> Left: Pre-operative CT, sagittal. Almost complete erosion of the body of C2. **Middle:** Preoperative CT, coronal, demonstrating the extent of the bony erosion including the vertebral body and left articular pillar **Right:** pre-op diagnostic MRI demonstrating metastasis in C2



<u>Figure 2</u> Left: 3D rendering of planned surgical resection. **Middle:** 3D rendering with prosthesis in situ. **Right:** Manufactured titanium device in 3D printed skeletal model

Figure 3 Post-operative follow up imaging showing stable positioning of device

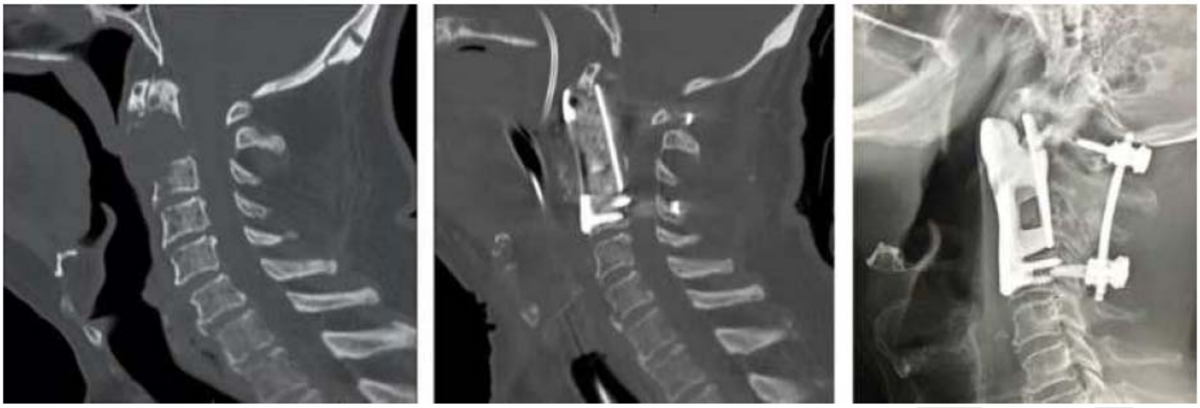


Figure 4 **Left:** Pre operative CT, sagittal, showing almost complete erosion of the body of C2. **Middle:** intraoperative CT showing graft-filled implanted device. **Right** Post-operative lateral X-ray showing stable device positioning.

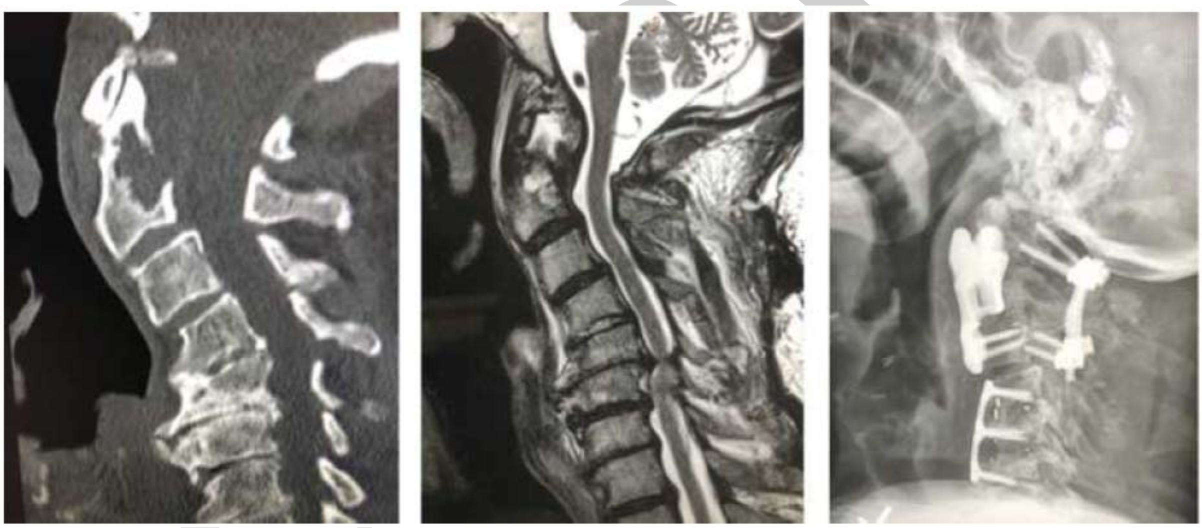


Figure 5 **Left:** sagittal CT reconstruction showing lytic destruction C2 vertebral body **Middle: MRI of** upper cervical spine showing extensive lytic pannus of C2 extending towards the craniocervical junction **Right:** post-operative lateral X-ray documenting device position.