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Tools and techniques

Designing patient-specific 3D printed devices for posterior atlantoaxial transarticular fixation surgery

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ABSTRACT

Atlantoaxial transarticular screw fixation is an effective technique for arthrodesis. Surgical accuracy is critical due to the unique anatomy of the atlantoaxial region. Intraoperative aids such as computer-assisted navigation and drilling templates offer trajectory guidance but do not eliminate screw malposition. This study reports the operative and clinical performance of a novel process utilising biomodelling and 3D printing to develop patient specific solutions for posterior transarticular atlantoaxial fixation surgery. Software models and 3D printed 1:1 scale biomodels of the patient's bony atlantoaxial spine were developed from computed tomography data for surgical planning. The surgeon collaborated with a local medical device manufacturer using AnatomicsC3D to design patient specific titanium posterior atlantoaxial fixation implants using transarticular and posterior C1 arch screws. Software enabled the surgeon to specify screw trajectories, screw sizes, and simulate corrected atlantoaxial alignment allowing patient specific stereotactic drill guides and titanium posterior fixation implants to be manufactured using 3D printing. Three female patients with unilateral atlantoaxial osteoarthritis were treated using patient specific implants. Transarticular screws were placed using a percutaneous technique with fluoroscopy and neural monitoring. No screw malposition and no neural or vascular injuries were observed. Average operating and fluoroscopy times were 126.0 ± 4.1 min and 36.7 ± 11.5 s respectively. Blood loss was <50 ml per patient and length of stay was 4–6 days. Clinical and radiographic follow up data indicate satisfactory outcomes in all patients. This study demonstrates a safe, accurate, efficient, and relatively inexpensive process to stabilise the atlantoaxial spine using transarticular screws.

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1. Introduction

The first description of the posterior atlantoaxial transarticular technique was described by Magerl and Seeman in 1979 [1]. Biomechanical studies have shown that transarticular screws stabilise the atlantoaxial spine by reducing anteroposterior translational and rotational movement [2–5]. Combining atlantoaxial transarticular screws with posterior element fixation significantly improves stabilization by reducing flexion and extension movement across the joint [2,6,7]. The increased stability allows for immediate ambulation with minimal head support and achieves bony fusion close to 100% [8–11].

However, transarticular screw placement is technically demanding due to the unique anatomy of the upper cervical spine and risk of spinal cord or vertebral artery (VA) injury [12,13]. A detailed appreciation of patient anatomy is necessary to determine the patient's suitability for transarticular screws and plan appropriate screw trajectories [14].

Studies of atlantoaxial bony and vascular anatomical variations using computed-tomography (CT) reveal that the size, path, and location of the VA cannot be precisely predicted using bony landmarks alone on radiography [15]. In cases of anatomic osseous abnormality, transarticular screw placement is considered challenging and even dangerous [16,17].

Intraoperative devices such as aiming tools [18–20], three dimensional (3D) CT based stereotactic guidance [17,21], patient specific drill guides [22–26], and robotic assistants [27] have been developed to minimise surgical frustration and reduce iatrogenic complications. However, these devices are limited by increased radiation exposure [28,29], relative inaccuracy [17], high cost, long operating time, and the need for additional sterilised accessories

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and consumables, which potentially affect the ergonomics of the operating theatre [29–31].

To address these issues, we developed a process to support the patient and surgeon from the initial consultation to the operating theatre to achieve optimal and safe atlantoaxial fixation. This study considers the design, manufacture, surgical use, and performance of biomodelling [32] and 3D printed patient specific implants (PSI) against alternate surgical aids for posterior atlantoaxial transarticular fixation surgery.

2. Materials and methods

2.1. Patient selection

After obtaining approval from the ethics committees at our institution, a retrospective review of the medical record and hospital spine registry was performed. Three patients were identified who presented between 2015 and 2016 with unilateral atlantoaxial osteoarthritis (Table 1) who had failed non operative therapy. These patients subsequently underwent posterior atlantoaxial fixation surgery using a PSI with C1-C2 transarticular and C1 posterior arch screws.

2.2. Surgical planning

Patients underwent a high resolution CT scan before surgery. CT bone images were exported in DICOM format to a surgical planning and biomodelling software suite (AnatomicsC3D, Anatomics Pty Ltd, St Kilda, Victoria, Australia) for analysis. A patient specific 1:1 scale biomodel (Fig. 1) of the occiput-C4 were manufactured from polymerised layers of acrylate resin using a 3D printer (printer name). The surgeon used the biomodel to develop a surgical plan to restore anatomical alignment and stabilise the atlantoaxial spine.

The surgeon collaborated with design engineers from a local medical device company (Anatomics, St Kilda, Melbourne, Australia) using proprietary software (AnatomicsC3D) to design a patient specific implant (PSI) (Fig. 3A). The implant was designed to fix the posterior elements of the atlantoaxial spine with two C1-2 transarticular screws and posterior C1 arch screws. The surgeon specified the desired atlantoaxial alignment, screw sizes, screw entry points, and screw trajectories which were simulated and verified using AnatomicsC3D. A second biomodel with corrected C1-C2 alignment was also manufactured for intraoperative stereotaxy (Fig. 2).

Fig. 1. Occipitocervical biomodel: Pre-operative 1:1 scale biomodel of patient's occipitocervical spine demonstrating unilateral C1-C2 subluxation.

The planned transarticular screw specifications were used to manufacture a stereotactic drill guide (Fig. 4A) using a selective laser sintering printer (Eosint GmbH, Krailling, Germany) from nylon-12. The ventral surface of the guide matched the bony contours of the posterior elements of the patient's axis to aid positioning during surgery. The guide was also designed to be fixed to the C2 spinous process to minimise movement during drilling.

The ventral surface of the PSI was also designed to match the bony contours of the atlantoaxial spine to aid positioning during surgery. The dorsal aspect of the PSI contained six fixation points.

Table 1
Patient data: Demographics, comorbidities, and pre-operative clinical findings.

Patient	1	2	3
Age	65	69	76
Gender	Female	Female	Female
BMI	32	28	24
Comorbidities	Hypertension; Atrial fibrillation	Hypertension	Hashimoto's Thyroiditis; Asthma; Rheumatoid Arthritis
Smoker	No	No	No
Presenting complaint	Right suboccipital pain	Suboccipital pain; right arm pain	Left suboccipital pain; left shoulder and arm pain
+ Neurology	Restricted neck Flex., Ext., Rot.; brisk reflexes; Hoffman's positive	Restricted Flex., Ext., and right Rot. of neck; diminished reflexes	Restricted Flex., Ext., and left Rot. of neck
C1-2 Facet Arthropathy (CT)	+ Right	+ Right	+ Left
C1-2 subluxation (CT)	–	–	+ Left
C1-2 fusion	–	+ Right	–
C2 nerve root compression (MRI)	+ Right	+ Right	+ Left
Non-operative therapy & outcome	6 month trial of analgesia, soft collar, C1-2 steroid injection; no relief	3 month trial of analgesia, soft collar, C1-2 steroid injection; no relief	3 month trial of analgesia, soft collar, C1-2 steroid injection; no relief
Pre-op VAS	5	8	4
Post-op VAS*	0	0	2

BMI – Body mass index; MRI – magnetic resonance imaging; SPECT – single photon emission computed tomography; VAS – visual analogue score
* VAS calculated at 3 months post-operation.

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