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ORIGINAL ARTICLE

Customised pre-operative cranioplasty to achieve maximal surgical resection of tumours with osseous involvement—a case series

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Abstract

Purpose Surgical resection with bony margins would be the treatment of choice for tumours with osseous involvement such as meningiomas and metastasis. By developing and designing pre-operative customised 3D modelled implants, the patient can undergo resection of meningioma and repair of bone defect in the same operation. We present a generalisable method for designing pre-operative cranioplasty in patients to repair the bone defect after the resection of tumours.

Materials and methods We included six patients who presented with a tumour that was associated with overlying bone involvement. They underwent placement of customised cranioplasty in the same setting. A customised implant using a pre-operative imaging was designed with a 2-cm margin to allow for any intra-operative requirements for extending the craniectomy.

Results Six patients were evaluated in this case series. Four patients had meningiomas, 1 patient had metastatic breast cancer on final histology, and 1 patient was found to have an intra-osseous arteriovenous malformation. Craniectomy based on margins provided by a cutting guide was fashioned. After tumour removal and haemostasis, the cranioplasty was then placed. All patients recovered well post-operatively with satisfactory cosmetic results. No wound infection was reported in our series.

Conclusion Our series demonstrate the feasibility of utilising pre-designed cranioplasty for meningiomas and other tumours with osseous involvement. Following strict infection protocols, minimal intra-operative handling/modification of the implant, and close follow-up has resulted in good cosmetic outcomes with no implant-related infections.

Keywords Cranioplasty · Osseous tumours · Decompressive craniectomy

Introduction

Primary and secondary tumours of the brain may often involve the adjacent bone. Meningiomas are the most common primary brain tumours, accounting for nearly 34% of all central nervous system tumours [17, 20, 22]. They often occur most frequently on the convexity and the parasagittal locations. Bony changes are often associated with these tumours. This could be due to hyperostosis of the overlying bone or due to a direct invasion of the bone by the tumour [17, 22]. Metastasis from any primary neoplasms such as lung, breast, and prostate cancer may lead to osseous deposits within the skull or dura/parenchymal deposits with involvement of the adjacent bone [5, 6, 15].

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Depending on the pathology of such tumours, surgical resection with bony margins would be the treatment of choice. Bone that is known or suspected of being invaded, for example through pre-operative contrast-enhanced imaging, PET imaging, or intra-operative 5-ALA should be removed [7, 12], when this can be done safely. Intra-operatively, this bony defect can be reconstructed with a titanium mesh or mouldable bone cement. However, the cosmetic result may not be optimal. By developing and designing pre-operative customised 3D implants, the patient can undergo resection of meningioma and repair of bone defect in the same operation.

Cranioplasties using a variety of materials such as titanium, polyetheretherketone (PEEK), and polymethylmethacrylate (PMMA) have allowed neurosurgeons to develop customised implants for bone defects after decompressive craniectomy for ischaemic stroke, trauma, or infection [1, 8, 10, 18]. Cranioplasty not only assists with the restoration of mechanical protection of the brain, but it also restores intracranial physiology. Applying similar concepts to the patients

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requiring resection of disease bone during tumour resection, customised cranioplasty implants allow restoration of skull integrity without needing a second operation.

There have been few case reports in literature demonstrating the feasibility of simultaneous tumour resection and cranioplasty. Ben-Shalom et al. have recently described a single surgeon experience of 56 patients [2] undergoing prefabricated single-stage cranioplasty in patients with tumours. However, there is a lack of availability of a method that can be generalised to all patient population presenting with such tumours.

In this case series, we present our experience with customised cranioplasties for patients undergoing resection of tumours and resultant bony defect. We present a generalisable method for designing pre-operative cranioplasty in patients with such pathology.

Materials and methods

Patient recruitment

For this case series, we included six patients who presented with a tumour that was associated with overlying bone involvement. These patients were evaluated and planned for resection of the primary lesion with the overlying diseased bone. They would undergo a customised cranioplasty implant in the same surgical procedure.

Development of customised implants

A dedicated CT head scan with a "bone sequence" (120 kV, 199 mAs, 1000 ms; width 3874, level 950) with thin helical slices (≤ 1.0 mm) was performed for all these patients. The appropriate Digital Imaging and Communications in Medicine (DICOM) file is downloaded from the picture archiving and communication system and sent over to an external 3D manufacturing company (Cavendish ®, UK). A virtual 3D model of the skull is created and sent back to the primary neurosurgeon for evaluation. Comparing the pre-operative MRI and CT scan, the surgeon decides the extent of bony resection. A customised implant is designed based on the boundaries provided by the neurosurgeon with a 1–2-cm margin to allow for any intra-operative requirements for extending the craniectomy. The choice of material was either titanium or PEEK. The latter was preferred if there was a higher chance of leaving a residual tumour behind to facilitate subsequent radiological surveillance. Further modifications can be carried out prior to implant printing based on individual surgeon's preference. A cutting guide with a resection margin based on surgeon's preferences (typically 1–2 cm) is provided to allow for accurate craniectomy margins intra-operatively. An upward pointing arrow on the cutting guide allows for accurate orientation of the cutting guide.

The patient details, which will be permanently embossed on the plate for identification, are then added to the inside of the plate. A grid of 2-mm holes with 15-mm separation is added across the plate and its position is manually adjusted to achieve sufficient coverage and even spacing for fluid transfer and soft tissue attachment. Screw holes for implant fixation are then positioned approximately half-distance of the implant-skull overlap to secure the plate flat and evenly on the bone defect. Screw hole countersinks specific for the screws used to secure the plates are placed.

Surgical procedure

Pre-operative antibiotics are administered for all patients within 30 min of skin incision. The incision and surgical approach are decided based on the location of the meningioma. An incision lying directly over the cranioplasty is avoided. After raising the skin flap, the cranioplasty guide is placed on the bone and the outline is marked using a sterile marker. A craniectomy is performed using a high-speed cutting drill in a standard manner following the outline. The craniectomy may be extended if there is evidence of diseased bone on direct visual inspection. However, care is taken that further extension of bone removal is still incorporated within the additional 2-cm margins to allow for placement of the implant. The standard debulking and resection of the meningioma with the overlying dura are carried out. In accordance with the common principles in implant surgery, staff present in the operating theatre is minimised, and care is taken to handle the plate as little as possible, and only after changing to new sterile gloves. The cutting guide and the plate are sterilised separately. This allows the surgical team to only open the plate from its sterile packaging when the surgical field is ready for the implant to be placed. Any contact of the plate with wound edges is prevented during the surgery. The cranioplasty implant is then placed as an onlay design and secured with titanium screws. A subgaleal drain is avoided. In our institution, post-implant procedures such as cranioplasty and ventriculoperitoneal shunt, patients receive three doses of IV flucloxacillin (alternatives if they are allergic to penicillin). Any further antibiotics, in some cases for 48–72 h, are left to the discretion of the neurosurgeon in charge of the case. After discharge, regular checks are carried out with patients via telephone consults to ensure no wound issues have emerged. The wound is reviewed in the clinic at 10–14 days post-operatively where the sutures/staples are removed.

Case series

Case 1

A 48-year-old lady presented with a growing lesion on the forehead in the midline. She was allergic to gadolinium, so a CT scan with contrast was performed. CT revealed (Fig. 1A) a 60 × 36-mm lesion within the frontal bone, with expansion of the diploic space with preserved vascular channels (Fig. 1B). The craniectomy was performed based on this boundary, straddling on either side of the sagittal sinus. The titanium cranioplasty was then placed over the craniectomy defect with screws. A post-operative scan showed a satisfactory placement of the titanium cranioplasty. Figure 1C shows a scout image taken during the post-op scan, displaying the placement of cranioplasty. The histology was consistent with an intra-osseous meningioma WHO Grade 1.

Case 2

A 45-year-old gentleman presented with two episodes of generalised tonic–clonic seizures at his local hospital. A CT brain and contrasted MRI brain (Fig. 2A) revealed the presence of 64 × 54 × 54-mm left frontal convexity extra-axial lesion with surrounding perilesional oedema. Using the cutting guide, craniectomy was performed to excise the intra-osseous component with 1.5-cm margin. The tumour was excised. The titanium implant was placed and secured with titanium screws. A standard skin closure was performed. A post-operative scan (Fig. 2B) showed a satisfactory placement of the titanium cranioplasty. A 6-month follow-up MRI did not show the residual or recurrent tumour and the patient continued to be well and seizure-free.

Case 3

A 63-year-old man presented with a growing lump on the scalp over the vertex. A CT brain and contrasted MRI brain (Fig. 3A) revealed a 52 × 34-mm mass superior to the left frontal lobe which involved the overlying frontal and parietal bones and displaced the falx to the right. The radiological findings were consistent with those of a parasagittal meningioma. Due to the presence of sagittal sinus involvement, it was expected that a residual tumour would be left behind. To prevent imaging artefacts during follow-up, PEEK was chosen as the choice of material for cranioplasty. Using the cutting guide, craniectomy was performed to excise the intra-osseous component with 1-cm margin (Fig. 3B). The patient has remained well, and the surgical wound healed with no evidence of infection.

Case 4

An 82-year-old gentleman was known to neurosurgery for large left convexity meningioma for which he had undergone resection 7 years prior to this presentation. He was on surveillance imaging which showed a multifocal recurrence—left parafalcine lesion 14 × 10 mm within the resection cavity, left frontal convexity 9.5 × 6.5 mm, and another left convexity lesion 13 × 6.5 mm. Due to the need for follow-up in view of the atypical nature of the tumour, PEEK implant was used. The patient has remained well with no evidence of infection. The surgical site has healed well.

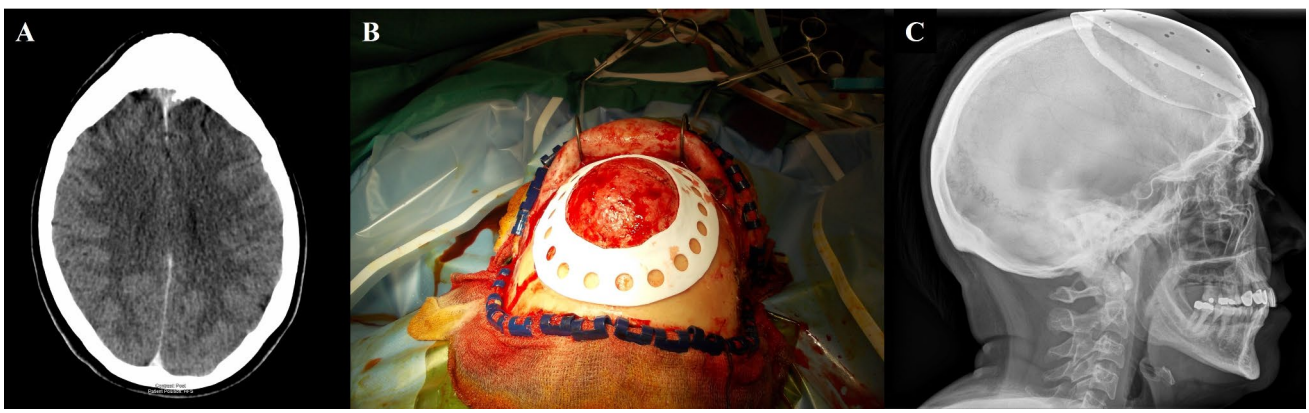

Fig. 1 **A** An axial section showing frontal bone lesion with expansion of the diploic space. **B** A cranioplasty guide placed to mark the intended craniotomy. **C** A scout image taken during the post-op scan, displaying the placement of cranioplasty

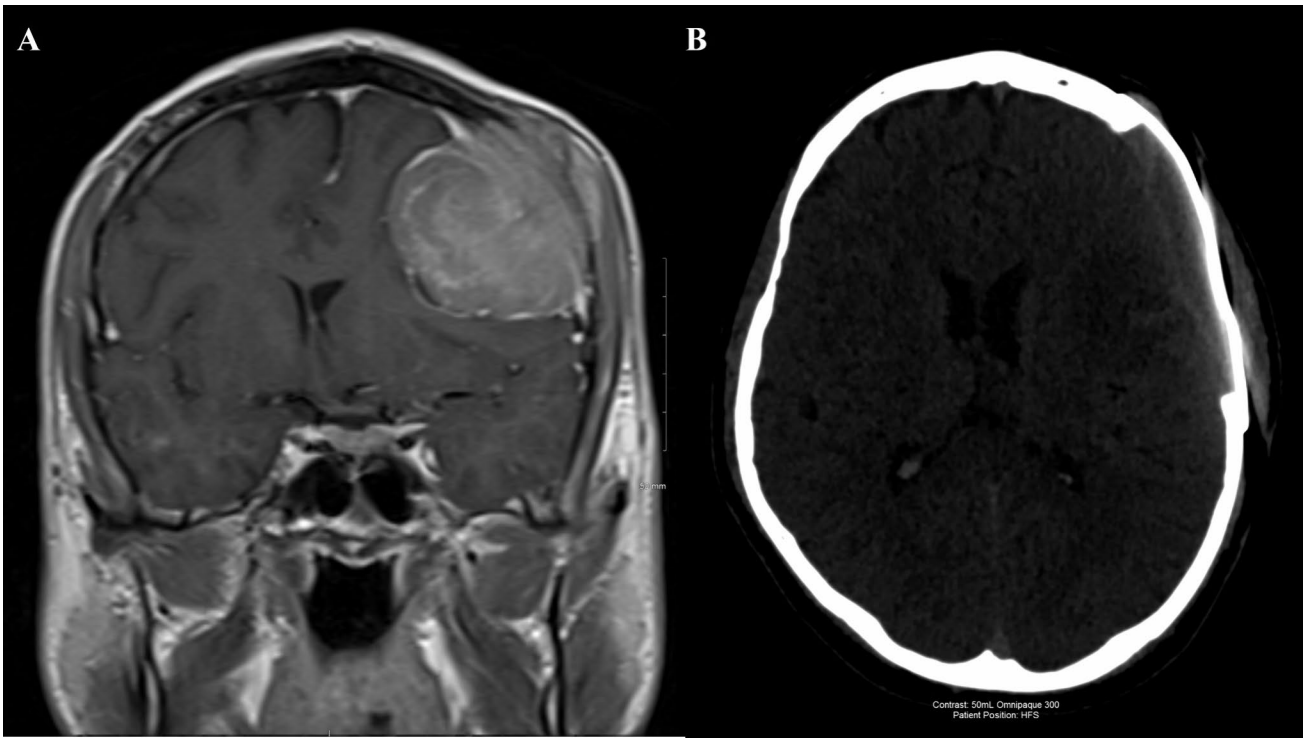

Fig. 2 **A** A coronal MRI slice showing the presence of a large convexity meningioma with osseous involvement. **B** A post-operative scan showed a satisfactory placement of the titanium cranioplasty

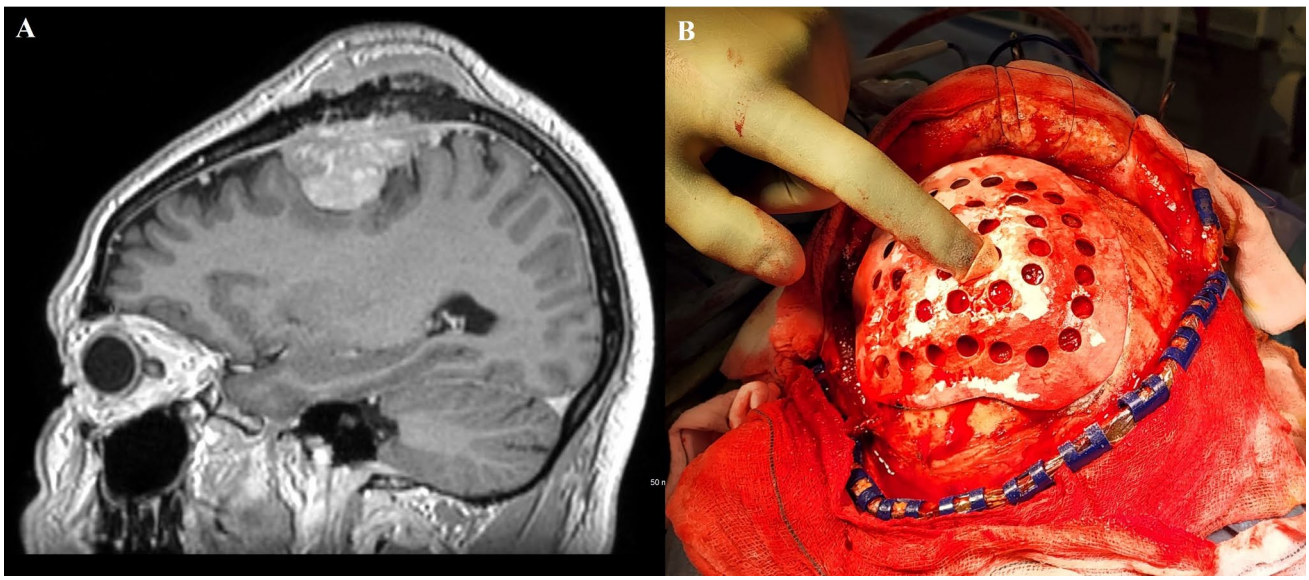

Fig. 3 **A** A contrasted MRI brain showing a 52 × 34-mm mass superior to the left frontal lobe which involved the overlying frontal and parietal bones and displaced the falx to the right. **B** Using the cutting guide, craniectomy was performed to excise the intra-osseous component with 1-cm margin

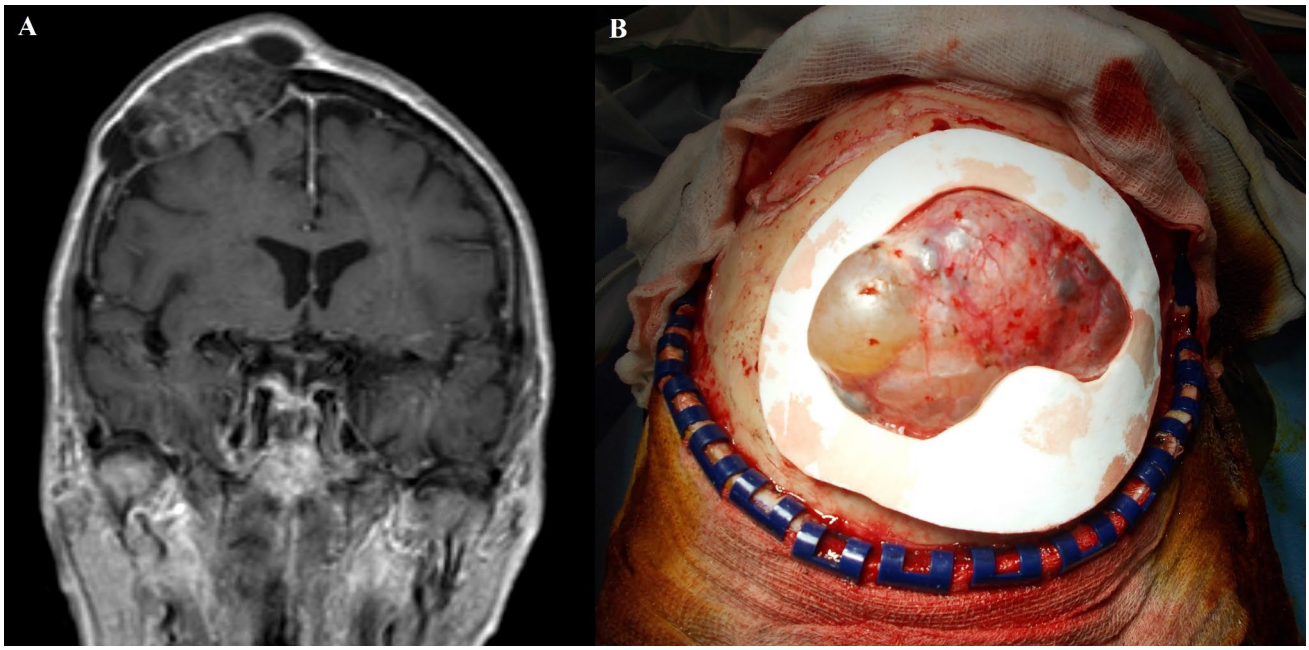

Fig. 4 **A** A coronal MRI showing the presence of destructive lesion involving the calvaria. **B** Use of a cutting guide to decide the extent of craniectomy

Case 5

An 84-year-old lady with a known history of breast cancer presented with a growing lump in the right frontal region. A CT and MRI demonstrated a lytic lesion (Fig. 4A) around her right frontal bone with moderate contrast enhancement. In view of the previous history of the breast cancer, the patient was counselled for craniectomy and resection of the tumour, with replacement of the bone with a customised titanium cranioplasty. Figure 4B shows the use of a cutting guide to decide the extent of craniectomy. The final histology was consistent with metastatic breast carcinoma. The patient was not keen for further scans as she was well with good wound healing. She was discharged to her local hospital for further follow-up in view of her recurrent cancer.

Case 6

A 37-year-old gentleman presented with a growing lump on the right side of the head. A CT and MRI revealed a $16 \times 16 \times 8$ mm relatively heterogeneous and partially lucent lesion within the right frontal bone, which was mildly expansile but well defined. In view of the pain associated with the lesion, the patient decided for craniectomy and removal with a pre-designed cranioplasty. The patient remained well post-operatively with satisfactory post-operative imaging. Histology was consistent with that of an arteriovenous malformation.

Discussion

The availability of 3D printing and variety of materials has allowed customisation of cranioplasty for various indications. Its use in decompressive craniectomies following a stroke or trauma has been well proven in the literature, including maximising recovery potential, improved functional and cognitive gains, enhancement of quality of life, and restoration of cosmesis [8, 11, 18]. However, there is a paucity of data where simultaneous cranioplasty after the tumour resection is concerned. To achieve success in this procedure, it is vital to accurately plan the intended craniectomy margins with the possibility of some modification of these margins depending on the intra-operative findings. 3D modelling based on pre-operative CT scans allowed the authors to accurately plan the margins of the desired craniectomy. The presence of a cutting guide with markers for intra-operative orientation assists in avoiding inadvertent errors of orientation of final cranioplasty. The addition of margins in the initial planning further allows modification of surgical plans due to intra-operative findings. With progress in computing methodologies, the existence of augmented and mixed reality software and 3D visualisation has become easy. The authors recommend the usage of an intra-operative cutting guide as described to prevent errors during planning of craniectomy and placement of cranioplasty to allow for the best fit while minimising intra-operative implant handling.

Our surgical technique varies from what has been previously published where the craniectomy is performed prior to the use of a cutting guide. In those studies, [2, 3, 10, 16], the craniectomy is performed using margins identified based on neuronavigation. The cutting guide is then placed to further modify the margins to allow for the placement of an oversized implant. Using a cutting guide to define the margins of the craniectomy upfront prevents erroneous bone removal which could lead to difficulties in placing the implant properly. The additional 2-cm margin (this can be increased or decreased depending on surgeon preference) ensures that further bone removal does not have a deleterious impact on the implant fit. The previous studies and case reports have also looked at drilling the implant intra-operatively to improve the fit. However, minimal implant handling intra-operatively should be done to avoid increased risks of infections.

All our patients did not have any implant-related infections in the acute post-operative period or during long-term follow-up (at least 6 months in all patients). This was despite patients being on dexamethasone pre-operatively. Case 4 was a redo surgery and the surgical wound healed well without evidence of any delayed infections. Lönnemark et al. [10] recently reported a high rate of implant failure in patients undergoing simultaneous cranioplasty with tumour resection. Six patients out of 36 patients had implant-related infection requiring removal, with a mean time to infection being 220 days. They could not find significant differences between different cranioplasty but there was a trend toward earlier failure and higher failure rates when porous polyethylene was used. The authors acknowledge that the infections can occur at a much later stage. A larger case series with a much longer follow-up will be needed to ensure that these results are reproducible.

As previously mentioned, strict infection control protocols have been instituted in our institution as we perform a high number of cranioplasties for decompressive craniectomies. Pre- and post-operative antibiotics, minimal intra-operative personnel, and minimal handling of the implant during the surgery could be factors in preventing implant failure. It would be not possible to extrapolate the data from decompressive craniectomies due to the difference in pathology and staged procedure. Although initially thought that an early cranioplasty is associated with a higher risk of infection, a multicentre prospective cohort study found no difference in infection rates in early cranioplasty compared with a late one [4, 14]. The current recommendation to prevent post-operative infections is the administration of antibiotics within 30 min of skin incision. In our series, antibiotics were given for a minimum of 24 h (as per institution guidelines), which may be extended to 72 h on surgeon's discretion. Paredes et al. [13] analysed the risks of surgical site infections using various protocols of antibiotic administration including short- and long-term administration of post-operative antibiotics. The rates of post-operative infection ranged between 4.4 and 21.9%. Repeated surgeries and previous infections have been implicated as causes of increased risks of surgical site infections. The authors acknowledge that this case series is too small to make any meaningful conclusions regarding infection and further studies will be required to understand the rate of implant failure in simultaneous cranioplasties.

The choice of material for cranioplasty has always been a subject of debate [9, 19, 21]. Surgeon preferences, timing of availability of implant, and cost are some of the factors that may contribute to the choice of implant. In our case series, we have used titanium and PEEK. Titanium implants are well known for their biocompatibility and being mechanically resistant. It has been shown to be associated with better cosmetic and functional outcomes. PEEK is bio-inert and mechanically resistant as well. However, there is a lack of long-term studies and in-house sterilisation is required. The lack of imaging artefacts with PEEK makes it an implant of choice when regular imaging surveillance is required. However, it is associated with higher costs and longer implant preparation time. The authors propose that using the protocol described above, the procedure can be generalised to any implant material. The authors would like to highlight that it would not be possible to modify implants made from titanium. If significant intra-operative changes in craniectomy are expected, other implant materials should be considered. Long-term outcomes with regard to implant infection or requirement of post-operative treatment with radiotherapy remain to be explored.

In our institution, patients with cranioplasty are regularly followed up by specialist neurotrauma nurses. Pre-operative cranioplasty counselling, regular telephone consults, and clinic wound review post-operatively are carried out by them. This is to ensure that any wound issues are picked up early and interventions can be performed in a timely manner. Although the patients did not develop any infections, the authors believe that dedicated patient education and close follow-up will allow the clinicians to prevent debilitating infections and implant failure.

While this study shows the possibility of simultaneous tumour resection with cranioplasty, some institutions may not have the capacity to perform this. The presence of malignant tumours may require time-sensitive resection, and it should not be delayed awaiting a customised cranioplasty. A staged resection with subsequent cranioplasty remains a reasonable option.

In this study, we did not quantify the experience of the patients. All patients reported during their clinic follow-up that they were satisfied with their cosmetic outcomes. Further studies are required to understand the patient experience in simultaneous cranioplasty better.

Conclusions

The authors present a generalisable method using a cranioplasty cutting guide for simultaneous resection of tumours with osseous involvement and cranioplasty. This allows maximal surgical resection of the tumour and restoring cosmesis. Using a cutting guide and minimal intra-operative handling of the implant will reduce the risks of infection and implant failure.

Author contribution SJ was responsible for the collection of data, analysis of images, and follow-up for the patients. AH, TS, and PH were responsible for the initial conceptualisation and evaluation of data. NO and KG were instrumental in patient follow-up and recording of outcomes. IT supervised the entire study and completion of this manuscript.

Data availability This declaration is not applicable.

Code availability This declaration is not applicable.

Declarations

Ethics approval This declaration is not applicable.

Consent to participate All patients included in this study had consented to use of their anonymised images for purposes of research and publication.

Consent for publication All patients included in this study had consented to use of their anonymised images for purposes of research and publication.

Conflict of interest The authors declare no competing interests.

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