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Analysis of Surgical Management of Calvarial Tumours and First Results of a Newly Designed Robotic Trepanation System

Abstract

This study was performed to evaluate the surgical strategy in patients with calvarial tumours, in order to design and modify a robot-assisted trepanation system. A total of 75 patients underwent craniectomy for the treatment of calvarial tumours during the 10-year period from 1993 to 2002. The patients' complaints, the size, location and histology of the tumour, and the various cranioplasty techniques used were analysed retrospectively. In a second procedure several craniectomies at typical locations according to the study's results were performed in a laboratory setting using a hexapod robotic tool, constructed at the Helmholtz-Institute, RWTH Aachen University, and plastic model heads. The workflow was documented and the reproducibility and the accuracy of the procedure were registered. A total of 83 surgical procedures were performed on 75 patients. The majority (87%) of lesions treated surgically were located in the frontal, temporal and anterior parts of the parietal region. Histological examination revealed benign lesions in 66% of the patients and dural involvement in 46%. According to these results craniectomies were performed using the robotic system. Mean positioning accuracy of the robotic system while milling was 0.24 mm, with a standard deviation of 0.04 mm, and maximum error under 1 mm. Craniectomies leaving a 1-mm layer of the tabula interna intact to ensure a healthy dura were performed in several regions successfully. The majority of calvarial tumours, requiring surgical treatment in our patients, were located in cosmetically relevant areas in which drilling can be carried out with the robotic trepanation system. Consequently, the surgical approach had to be planned carefully in order to achieve a good cosmetic outcome.

Key words

Trepanation · robotic assisted surgery · calvarial tumours · neurosurgery

Introduction

Osseous tumours of the skull are rare entities characterized by a large variety of histological findings, as described by Arana et al. [1,2], Ciray et al. [3], and Hunt et al. [4]. The majority of such tumours encountered in the field of neurosurgery are either meningiomas or metastases [5,6]. Symptoms include changes in the patient's appearance and neurological deficits due to intracranial expansion of the tumour. Although resection of the lesion is always the primary objective of surgical treatment, increased attention has also been devoted recently to restoration of the concomitant defect leading to a cosmetically satisfying outcome [7–10].

Drilling of the skull by means of a robotic system has proved to be a valuable surgical technique for precise insertion of cochlea implants [11,12] or has been evaluated intraoperatively for the development of a system for craniotomy [13]. The craniectomy could be a new application for a robotic system in patients with

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osseous tumours, especially in cosmetically important areas of the skull.

The aim of this study, which is supported by the German Research Foundation (DFG) within the SPP 1124, was to evaluate osseous lesions with regard to location, histological findings and surgical management. Furthermore, first drilling tests with a plastic model head were carried out in a laboratory setting, according to the evaluated workspace area.

Patients, Materials and Methods

A total of 75 patients (54 females and 21-males) with a mean age of 57 years (range: 4 – 95 years) who had been treated surgically for calvarial tumours during the 10-year period from 1993 to 2002 were included in the study. The demographic data, clinical and pathological findings, and information on the preoperative diagnostic procedures used for surgical planning were obtained from the files. Lesions were classified according to their location, size and histology; cosmetic impairments were documented. The surgical management was analysed, with special emphasis on dural involvement and repair and the type of cranioplasty used. Fisher's exact test [14] was used to test for dependence in contingency tables; the level of significance was set at 0.05.

The data on location and size were also analysed to identify requirements for a hexapod robot system and to perform the first craniectomies in a plastic model skull. The robotic system used was a hexapod parallel robot with platforms of 440 and 200 mm in diameter; the legs could be varied in length from 430 mm to 580 mm. Preliminary tests have been conducted to evaluate the robotic drilling parameters and the accuracy of craniectomy in a laboratory setting with a plastic model head.

Several craniectomies were performed in typical locations, according to the statistical evaluation of calvarial tumours, in order to acquire data on accuracy and reproducibility. Furthermore, several robot settings differing in parameters such as speed of drilling and movement were evaluated and compared.

Results

A total of 83 surgical procedures were performed in 75 patients. Cosmetic changes of the cranial vault were detected in 46 % of the patients, whereas neurological deficits were diagnosed in only 13 %. Twenty-two percent of the patients complained of headaches at admission (Table **1**). Forty-five percent of the lesions were located in the frontal region of the skull.

The preoperative diagnostic work-up included CT or MRI in all patients; both were carried out in 39 patients. Starting in 1997, the technique of neuronavigation was used in 33 % of cases (n = 14). A total of 13 of the navigated lesions were located in the frontal and/or parietal region; half of them were small tumours below 2 cm in size. The mean size of the craniotomy performed was 4.5 cm overall (range: 1 – 17 cm). Infiltration of the dura was present in 46 % of the lesions. Sixty-three percent of the lesions with dural infiltration were meningiomas; the remainder consisted of metastatic lesions of the skull. Infiltration of venous sinuses was verified during surgery in 13 %. The correlation between histological classification of the tumour and the presence of dural or sinus infiltration was statistically significant (p = 0.047). As shown in Table **2**, a broad spectrum of pathology was encountered. The majority (66 %) of the lesions treated were benign lesions and tumours of the skull.

In 43 % of the patients with benign lesions, craniotomy and resection of the infiltrated part of the bone followed by reinsertion of the non-affected part was possible; acrylic bone cement was

Table **1** Symptoms and clinical findings in patients with osseous tumours on admission (*n* = 75)

		Patients	***%***
Cosmetic disfigurement	Localised swelling	38	46
	Palpable bone defect	3	4
	Skin infiltration	4	5
	No visible signs	38	46
Neurological impairment	Exophthalmos	7	8
	Headache	18	22
	Neurological deficits	11	13
	No neurological impairment	47	57

Table **2** Histological findings in resected lesions of the skull (*n* = 83)

			Number of lesions	***%***
Benign lesions	Fibrous dysplasia	10	18	22
	Encephalocele, cyst	3		
	Hyperostosis	2		
	Growth fracture	1		
	Bone cysts	1		
	Tuberculosis	1		
Benign tumours	Meningioma, benign	30	36	43
	Haemangioma	3		
	Astrocytoma	1		
	Multiple myeloma	1		
	Osteoma	1		
Malignant tumours	Adenocarcinoma metastasis	14	28	34
	Meningioma, malignant	6		
	Basal cell carcinoma	3		
	Breast cancer metastasis	2		
	Angiosarcoma	1		
	Metastasis, primary unknown	1		
	Malignant histiocytoma	1		
No differentiation	Malignant	1	1	1
Total		83	83	100

Table **3** Distribution of the osseous lesions of the cranial vault (*n* = 83)

Location	*Number of procedures*	*%*
frontal	37	45
parietal	23	28
temporal	12	14
occipital	6	7
periorbital	5	6
total	83	100

used in 46% of cases. In three patients, individually prefabricated titanium implants were inserted after resection of the tumour. In patients with small defects (i.e., less than 2 cm in diameter) without cosmetic relevance, cranioplasty was not performed.

Analysing the location of tumours, we were able to define a working space covering 87% of all lesions including the frontal, temporal and the anterior part of the parietal skull (Table **3**). Tumour diameter was greater than 6 cm in 16% of the patients, partly with several differently oriented bony surfaces to be drilled. Supine positioning intraoperatively was used in 86% of the lesions.

Owing to the cosmetic relevance of these tumours, navigational control and prefabricated cranioplasty were indicated.

Depending on the tumour location, some of the craniectomies were simulated using a hexapod parallel robotic system and plastic head models. A 1-mm layer of the tabula interna was planned to be left intact to ensure a healthy dura. The positioning and the progress of drilling were controlled by means of a navigated drilling tool fixed to the top of the robot. The drill used was a 6-mm cut drill. The mean positioning accuracy of robot was 0.24 mm, 0.04 mm standard deviation, and maximum error under 1 mm. The lines were 0.85 mm apart, and the speed of advancement was 3 mm per second. Accuracy of fiducial marker-based registration between the physical space of skull phantom and reconstructed 3D cranial model from CT was 0.53 ± 0.12 mm. The registration is performed in order to transform data from the preoperative planning to the robotic system (Fig. **1a**) [15,16]. After performed resection, with 1 mm safety distance from the dura planned, a layer of approximately 0.25 mm is noticeable (Fig. **1c**). A drill volume of 6500 – 7000 mm^3 was possible. A force of 20 N was possible; in practice, the mean force used was less than 2 N. The robotic system was able to create all of the craniectomies that were necessary according to the analysis of location of the calvarial tumours (Fig. **1b**).

Discussion

In this study osseous tumours and their surgical treatment were analysed in order to design a robotic trepanation system. Commonly accepted treatment strategies for osseous tumours include surgical resection of lesions causing neurological impairment, tumours displaying rapid growth and benign lesions accompanied by cosmetic disfigurement [17 – 20]. In this study 46% of the patients presented with swelling above the lesion. The diameter of this swelling was greater than 6 cm in 16%.

The majority of the lesions treated in this study were located in the frontal or parietal region; this correlated well with the findings of studies by Constans and Donzelli [5] and Wecht and

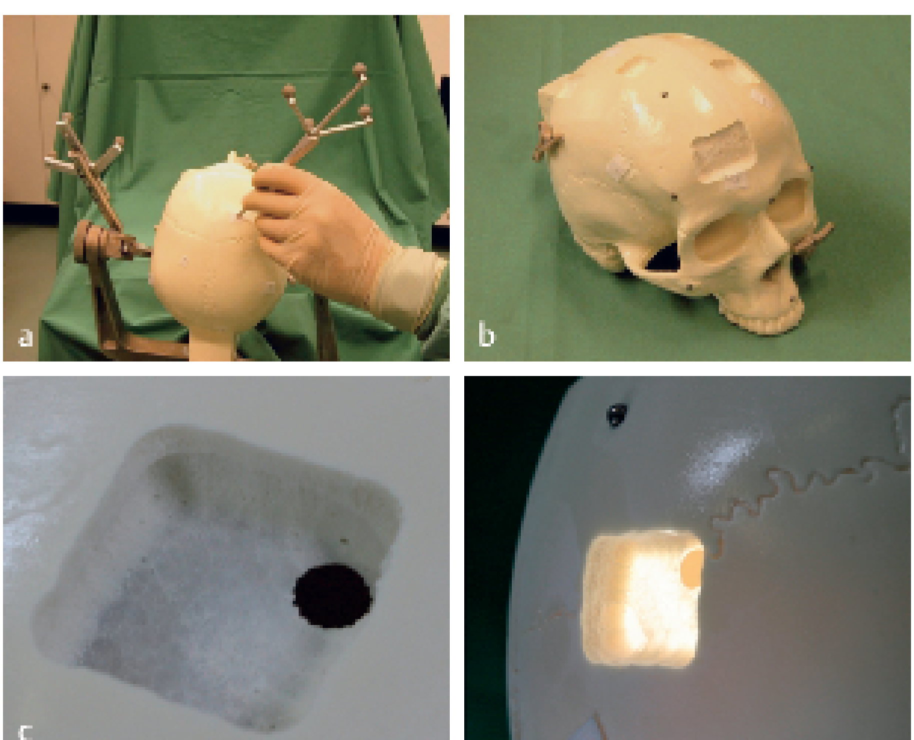

Fig. **1** **a** Registration of the head using implemented markers and a navigation system, allowing constant tracking of the drill. **b** Results after robot milling of several craniectomies according to the analysed data of osseous tumours. **c** Demonstration of a layer of the tabula interna. Drilling performed by the hexapod robot.

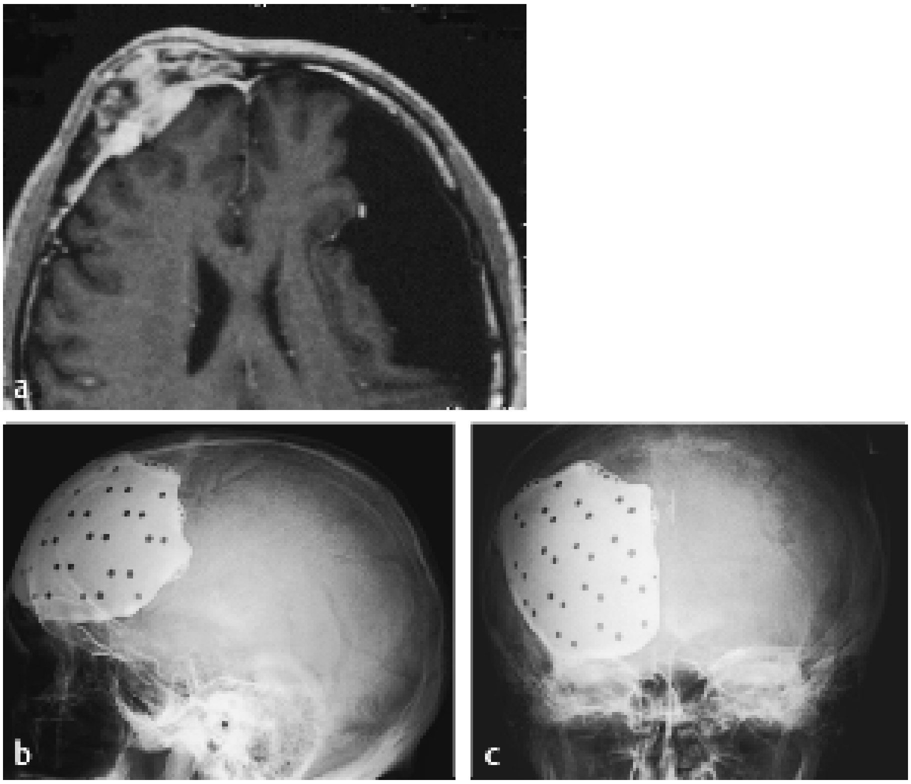

Fig. **2** **a–c** A 47-year-old male patient with enlargement of the skull and localised pain. No neurological deficits were noted at admission. MRI revealed a large tumour with enlargement of bone and dural infiltration. The tumour was resected in toto including a dural repair with fascia lata and cranioplasty with a prefabricated titanium implant. The lesion was classified histologically as a meningioma.

Sawaya [10]. In contrast, Artico et al. [7] found no preferred region of the skull for tumours in their study population.

The variety of histological entities found in our study is consistent with the findings of other authors [5,7,10]. In one case the pathologist could not classify the lesion definitively. This was consistent with the findings of Wecht and Sawaya [10], who reported five cases in which histological classification was impossible.

In contrast to Sekhar [9], who used fluoroscopy and preoperative scintigraphic scanning, in this study CT and MRI were employed, since the interpretation of the information in navigation is well established and necessary to control the robot intraoperatively.

Infiltration of the dura and/or the sinus was present in nearly twice as many patients as in other studies (46% vs. 20–26%) [5,7,10], mainly due to the large number of meningiomas found in our series. Sixty-three percent of the meningiomas and 31% of the metastases had already infiltrated into the dura. Of the patients with dural involvement, 19% exhibited infiltration of the sinus. Involvement of these structures required special surgical planning to prevent laceration of the dura and brain tissue. Furthermore, dural infiltration has important technical implications for the design of the robotic trepanation system, especially the distance from the healthy brain tissue.

Following resection of the infiltrated dura, the resulting defects were repaired. In our study autologous material was used for this purpose in the vast majority of cases. A similar management strategy was used in the studies of Artico et al. [7] and Constans and Donzelli [5]. In this study Lyodura® or Teflon® implants were employed in only two cases. We preferred to use autologous materials such as galea periosteum or muscle fascia, taken either from the temporalis muscle or the fascia lata, because these natural materials resemble normal dura more closely.

In patients with small lesions we performed only soft tissue replacement without cranioplasty, in common with Wecht and Sawaya [10]. Constans and Donzelli [5], however, never performed cranioplasty; they and others used acrylic bone cement to repair defects resulting from the excision of larger malignant lesions. A different method was described by Saringer et al. [20], who used individual carbon fibre polymer. The relationship between defect size and cranioplasty was statistically significant ($p = 0.043$).

In a large number of cases, therefore, cranioplasty is mandatory for cosmetic reasons, with the insertion of a prefabricated implant usually being the restoration modality of choice. Moreover, enhanced circulation and improved cognitive ability have been reported by Agner et al. [21] following the performance of cranioplasty to repair a large osseous defect.

In patients with larger benign lesions involving cosmetically relevant structures of the forehead and the face, we have found prefabricated titanium implants to be suitable, especially in cases where exact preoperative planning of the resection was possible as described by Eufinger et al. [22]. Fig. **2** shows a patient with a large meningioma extending into the frontal area of the face. Resection was followed by cranioplasty with a titanium implant; this resulted in a perfect cosmetic outcome. Since titanium implants are expensive, several authors have advocated the use of bone cement during elective cranioplasty.

Fig. **3** Hexapod robotic system in laboratory surrounding, placed beneath the patient's head with connected high-speed drill and navigational array (enlarged in Fig. **4**).

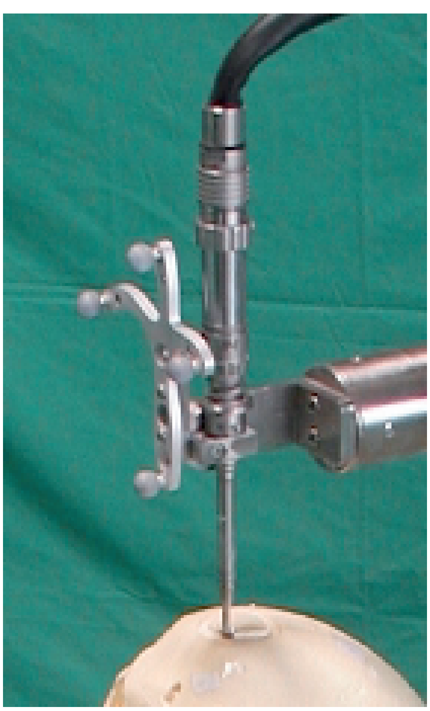

Fig. **4** High-speed drill and navigational array of hexapod robotic system.

In patients with skin involvement, a rotational skin flap or split-skin graft was put in place during the initial operation or during a second surgical procedure, as also mentioned by Constans and Donzelli [5] and Wecht and Sawaya [10]. Four patients with skin involvement were treated with a rotational skin flap.

Other authors [11 – 13] reported about drilling of the skull, whereby they used different robotic platforms. The hexapod robotic system we used demonstrated the ability to drill the calvaria accurately. Furthermore, it was possible to reach all necessary locations, based on the analysis of the lesions in this study. In this test setting the robotic system, with six degrees of freedom, performed a craniectomy by drilling the skull to a thickness of 1 mm to ensure a healthy dura in natural circumstances (Figs. **3** and **4**).

The potential advantages of robot-assisted resection are: precise drilling at different bone surface angles and the possibility of performing a planned resection and inserting a prefabricated alternative. Further drilling tests have to be done to refine parameters of the robotic system such as speed of advancement and temperature increase, with the danger of bone necrosis and a disturbed healing process of the bone, possibly influencing the cosmetic outcome.

Apart from these refinements we would state the following three preconditions:

a) Preoperative planning including an adequate diagnostic work-up is mandatory.
b) Navigational support has to be provided for the localisation and surveillance of the resection area.
c) The working range of the robotic system has to cover the entire region in question.

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