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Surgical navigation-assisted mandibular reconstruction with fibula flaps

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Abstract. The mandible has an important role in appearance and function. The aim of this study was to describe and evaluate surgical navigation-assisted mandibular reconstruction with the fibula flap. Patients recruited into the study had a custom dental splint fabricated to maintain the mandible in a fixed position. Later, the computed tomography (CT) scan, preoperative design, and operation on the mandible were done in the same position. At 1 week after surgery, a CT scan was done to evaluate the repeatability between the preoperative design and the postoperative result. Twenty patients were enrolled in this study. Good repeatability between the postoperative CT and the preoperative design was found. The repeatability between the preoperative plan and postoperative outcome was $79.1 \pm 8.6\%$ at within 1 mm, $87.1 \pm 6.7\%$ at within 2 mm, and $91.9 \pm 5.4\%$ at within 3 mm. From this study, it can be concluded that surgical navigation techniques can precisely transfer the preoperative design to the operation in mandible reconstruction with a fibula flap. This will assist the surgeon in achieving good cosmetic and functional outcomes.

Key words: mandibular reconstruction; surgical navigation; computer-assisted surgery; fibula flap.

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The mandible has an important role in facial harmony, mastication, speech, swallowing, support of the tongue base, and airway function. Jaw defects caused by a tumour or injury usually result in compromise of these functions, as well as facial aesthetics.[1,2] The utility of the free fibula osteocutaneous flap for mandibular reconstruction was recognized and subsequently popularized by Hidalgo in 1989.[3] The fibula flap is now used widely in mandibular reconstruction. Advantages include the ability to incorporate skin, muscle, and components of bicortical bone that can accurately reproduce the mandible. Comprehensive long-term follow-up studies assessing the cosmetic effect, speech, and deglutition have demonstrated satisfactory outcomes. Morbidity at the donor site has been described as 'mild'.[2,4,5]

Even though mandibular reconstruction with the fibula flap is now a common oral and maxillofacial surgical procedure, it is technically challenging and time-consuming. In addition to microvascular anastomoses, contouring of the flap must be precise to re-establish the form-and-function occlusal relationships of the mandible.[6]

To improve precision and simplify the surgical procedure, computer-assisted surgery (CAS) involving preoperative virtual planning and computer-assisted intraoperative navigation has evolved. Computerized navigation was first indicated for the resection of tumours in the craniomaxillofacial skeleton.[7] Based on identification of the tumour on computed tomography (CT) scans and the planned resection margins, the navigation probe is used intraoperatively to provide real-time feedback to the surgeon. Several studies have demonstrated the value of this technology in improving the precision with which tumours can be resected with safe margins while reducing the morbidity of unaffected tissues.[8,9]

The application of computerized navigation in surgery to the mandible is complicated due to its mobility. Unlike the rest of the craniomaxillofacial skeleton (which acts as one solid structure), the mandible is an independently movable body, so its synchronization with the pre-acquired CT image is more difficult.[10]

The aim of this study was to describe and evaluate a straightforward method for navigation-assisted mandibular reconstruction with a fibula flap.

Materials and methods

Ethical approval of the study protocol

The study protocol was approved by the institutional ethics committee. All patients provided written informed consent to participate in the study.

Patients

From November 2011 to September 2014, 20 patients with a lesion or defect of the mandible attending the study hospital were enrolled prospectively. Inclusion criteria were the following: partial resection of the mandible was indicated; reconstruction with a fibula graft was possible; the patient could wait 3–5 days for a design to be created; the patient agreed to the surgical team using a computer-assisted navigation method. Exclusion criteria were the following: operation time had to be controlled because of the general status of the patient; the patient could not wait 3–5 days for a design to be created; the patient had an advanced malignant tumour with a poor prognosis; mouth opening was limited, so making a dental splint was difficult. A preoperative incisional biopsy was done in order to obtain a pathological diagnosis. Reconstruction was indicated for all patients.

Surgical planning

All patients underwent preoperative spiral CT (helix with a slice thickness of 1.25 mm), which was repeated at 1 week after surgery (BrightSpeed 16; GE Healthcare, Buckinghamshire, UK). CT data were processed and transferred to SurgiCase CMF version 5.0 (Materialise, Leuven, Belgium) and iPlan CMF (Brainlab, Feldkirchen, Germany) via Digital Imaging and Communications in Medicine (DICOM) files for preoperative surgical planning and postoperative evaluation. The VectorVision system (Brainlab) was used for surgical navigation.

Preoperative design

A custom-made dental splint was fabricated. Once fitted, the mandible could be maintained in a fixed position. A high-resolution CT of the skull and fibula region was taken with the dental splint in situ. Two-dimensional CT data were saved in DICOM format. DICOM data were processed in SurgiCase CMF version 5.0 to generate accurate three-dimensional rendering of the bone contours. Virtual segmentation of the skull was undertaken to separate the mandible from the remaining parts of the skull.

Following standard principles, tumour resection was planned and the precise defect defined. Virtual design of the fibula flap involved segmentation, length of segments, angulation, and orientation to achieve the 'ideal' contour of the 'neo-mandible'. If distortion of the mandible due to the tumour was evident, the 'mirror' function was used to replicate the corresponding contralateral anatomical structure. If deformation was bilateral, the neo-mandible was guided by the position of maxillary teeth and the underlying skeletal base.

Surface data for all parts were exported into stereolithography (STL) files. Three-dimensional cylindrical-shaped objects in STL format were placed in a triangular pattern for use as reference points (Fig. 1). These were placed on the unaffected mandible on the facial aspect on both sides of the anticipated ostectomy. Cylinders were 3 mm in height and 2 mm in diameter. The three cylindrical-shaped objects were separated $\geq$1.5 cm to facilitate identification.[11]

STL data of segments with surface markers were imported into iPlan CMF, and merged into one object as the surface marker-assisted navigation plan.

Intraoperative navigation

Intraoperative navigation was undertaken using VectorVision (Brainlab). Preoperative preparation included matching the STL and CT in advance on iPlan (Brainlab) and exporting the file to the navigation workstation.

Under general anaesthesia, a reference frame with three light-reflecting spheres was fixed rigidly to the skull. Registration was completed through facial-surface imaging with the infrared ray (IR) emitter and IR receiver, as per the VectorVision protocol. Registration accuracies of the surgical area were verified automatically by the software, and registration errors were <0.7 mm in all cases. Also, surgeons could verify the actual surgical process on the virtual plan.[11]

Intermaxillary fixation was applied with a custom-made dental splint in situ (Fig. 2a). Under the navigation plan, all surface markers were located by the tip of a navigation probe. Holes were drilled in the mandible before osteotomy (Fig. 2b).

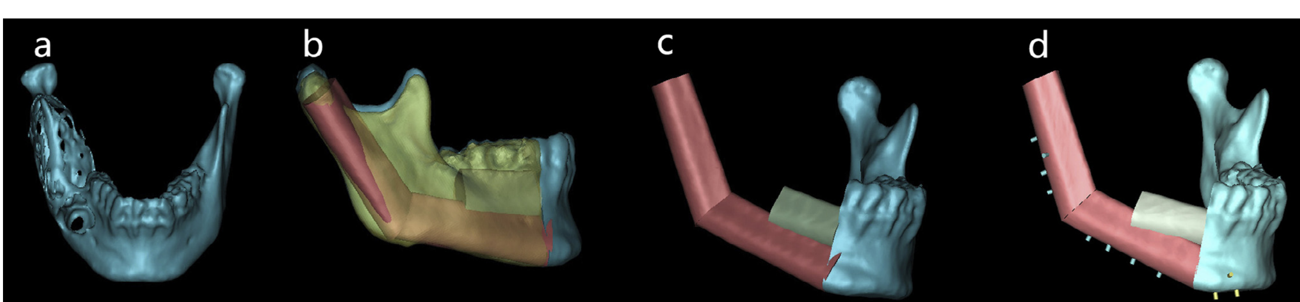

Fig. 1. Preoperative design procedure: (a) CT shows the tumour; (b) the 'mirror' function is used to replicate the corresponding contralateral anatomical structure and to design the fibula flap; (c) the fibula flap is designed; (d) cylindrical-shaped objects are placed on the residual mandible.

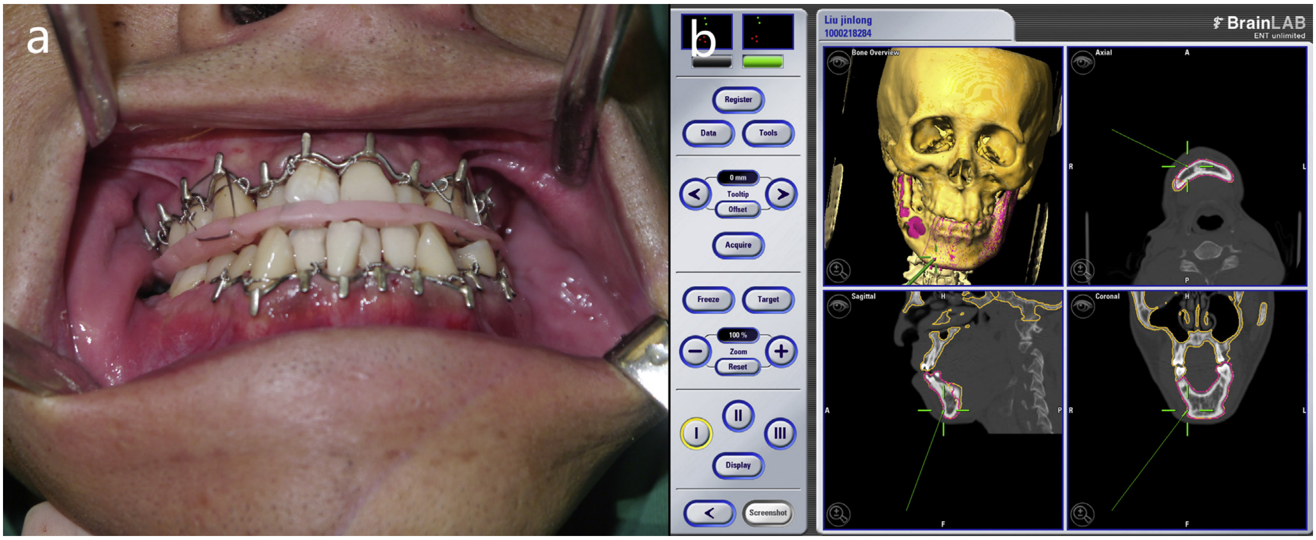

Fig. 2. (a) A dental splint is used to place the mandible in a unique position. (b) The navigation system is used to find the three cylindrical-shaped objects.

The line of the mandibulectomy was guided by the navigation system (Fig. 3).

A second surgical team concomitantly harvested the fibula flap. Segmentation and bevelling of the segments was completed according to the preoperative design in SurgiCase CMF. The fibula flap was transferred to the mandible. Before fixation of the fibula, the mandibular position was checked through the drilled holes over the mandible using the tip of the navigation probe. While insetting the fibula bone into the defect, the tip of a navigation probe was used to identify the inferior border and posterior border of the fibula and residual mandible (Fig. 4). After appropriate placement of the fibula bone in the intended position, rigid fixation with miniplates was carried out.

Postoperative evaluation

CT was done 1 week after surgery to assess the accuracy of the reconstruction. Three-dimensional rendering of bone contours was reconstructed from the postoperative CT and exported into STL files. Preoperative and postoperative data were imported into Geomagic Studio 2012 (3D Systems, Valencia, CA, USA). Manual and global registration functions were used to match the non-surgical parts of the two models. '3D comparison' was applied to illustrate the deviation from the preoperative planning in a deviation spectrum. The resulting error grade colour map provided a direct impression of the match between the preoperative plan and postoperative results (Fig. 5).

Results

Demographic data and clinical characteristics of the 20 patients (13 women and seven men, mean age 33 years (range 22–54 years)) are shown in Table 1. Among these patients, there were five with secondary mandibular defects, 10 with benign disease, and five with malignant disease.

All 20 patients underwent the described procedure successfully. In most cases, the

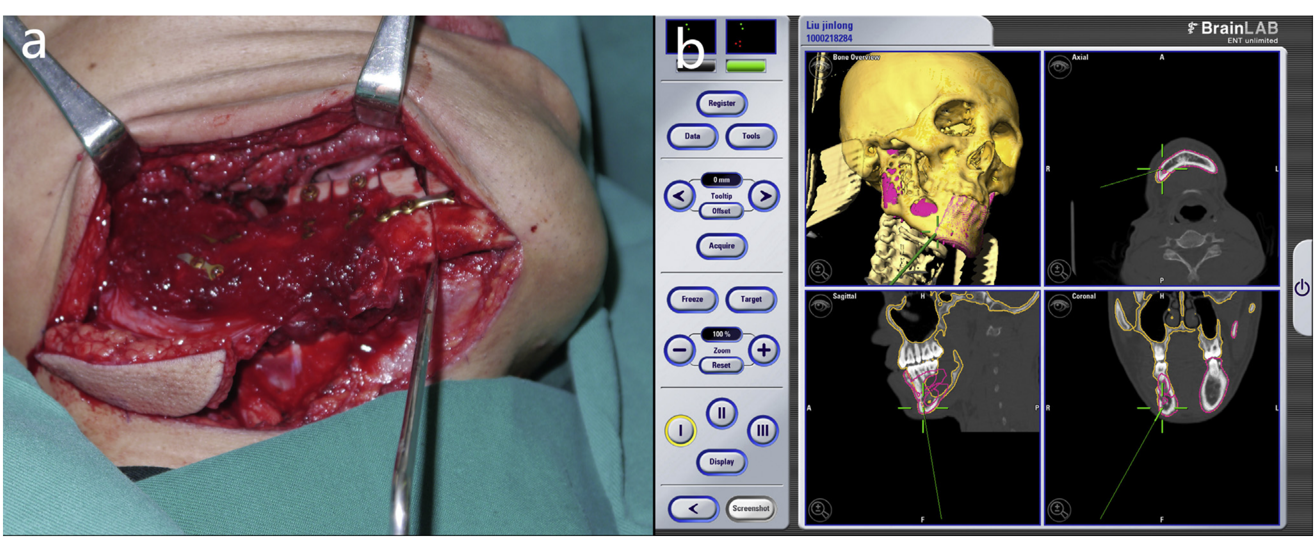

Fig. 3. (a) The tip of a navigation probe was pointed to the osteotomy line. (b) The position of osteotomy line was showed in the screen of navigation system.

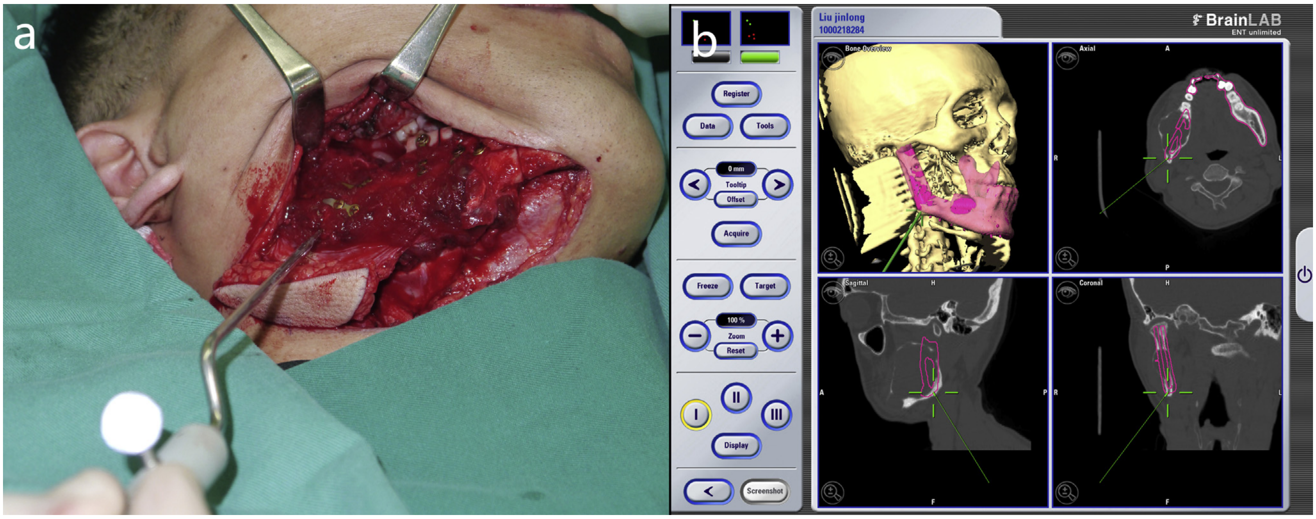

Fig. 4. The tip of a navigation probe was pointed to the angle of the new mandible. (b) The angle position of new mandible was showed in the screen of navigation system.

non-operated mandible remained stationary with the aid of the dental splint. In two patients, resection involved the anterior segment as well as bilateral bodies. These fibula flaps were difficult to fix in the designed position because the native mandibular segments were mobile.

The 20 cases showed good repeatability between postoperative CT and the preoperative design. Repeatability between the preoperative plan and postoperative outcome was 79.1 ± 8.6% at within 1 mm, 87.1 ± 6.7% at within 2 mm, and 91.9 ± 5.4% at within 3 mm.

Discussion

One of the greatest challenges in mandibular reconstruction is how to most accurately shape and fix vascularized bone flaps so that the symmetry and function of the face are restored optimally.[12] The mandible has a unique configuration that varies among individuals in curvature, length, and height. As well as re-establishing continuity, the aim of reconstruction surgery is to optimize facial contours and the occlusal relationship.[6] The development of CAS technology aids the execution and predictability of a precisely planned reconstruction.

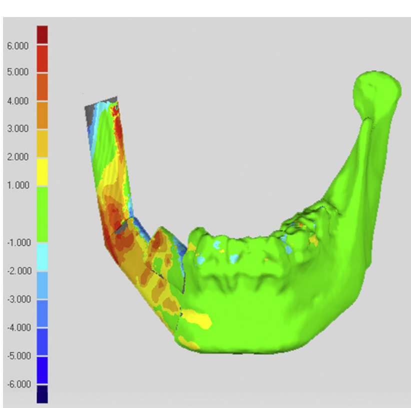

Fig. 5. A colour spectrum shows the deviation between the preoperative design and the postoperative result.

Recently, CAS has been used in the reconstruction of temporal bones as well as reconstruction of the orbital floor, condyle, and mandible. In terms of maxillofacial reconstruction, CAS is thought to (1) aid optimal preoperative planning with the virtual environment, (2) reduce the intraoperative time, and (3) aid precise implementation of the complex design in the surgical procedure.[13–15] These factors improve cosmetic and functional outcomes in patients with defects of the craniofacial skeleton. The procedure is reliant upon precise preoperative planning and accurate implementation of the plan.[16]

Various options are available for surgical planning and simulation, but precise transfer of data to the 'real' surgical environment appears to be challenging for surgeons. The two most popular methods for such a transfer are the use of a surgical-location splint and real-time surgical navigation.[17] Intraoperatively, the position of the template can be shifted or rotated, which can result in substantial deviation of the final position of the free-floating mandible remnants and fibula segments. To improve accuracy, a series of surgical templates can be produced. Separate splints can be used to guide lesion resection, fibula osteotomy, and graft positioning, but are time-consuming and expensive.[1]

Computer-aided navigation is a powerful tool that can be used to implement a surgical plan accurately. Computer-aided navigation is based on synchronization of the intraoperative position of the patient with the image of the patient's anatomy obtained previously by CT or magnetic resonance imaging.[10] Synchronization is realized through image registration and motion tracking.[16]

To enable navigation in relation to the lower jaw, three methods have been used. The first approach relies on maxillomandibular fixation, which is used to immobilize the mandible. The second and more commonly used approach is based on positioning of the mandible in a reproducible position that allows its synchronization, and is based on centric occlusion of the teeth or the use of special templates[8]. A third approach is to mount a special sensor frame onto the mandible, thereby allowing surgeons to track the position of the mandible optically and to compensate for its continuous movement during surgery[10]. Intraoperatively, the integrity of the mandible is destroyed after mandibulectomy. Hence, the third method could not be used for mandibular reconstruction. Maxillomandibular fixation could complicate tumour resection and mandibulectomy. Hence, the second method was modified for mandibulectomy and mandibular reconstruction in the present study.

In the present study, an individual dental splint was constructed to maintain centric occlusion. The patient wore the splint during the preoperative CT. With the splint in situ, synchronization of the intraoperative mandibular position with the preoperative image could be achieved

Table 1. Demographic data and clinical characteristics of the patients.

No.	Age, years	Sex	Diagnosis	Defect	Fibula segments	Repeatability within 1 mm (%)[a]	Repeatability within 2 mm (%)[a]	Repeatability within 3 mm (%)[a]
1	48	F	Ossifying fibroma	Left body	1	83.6	94.7	97.9
2	54	F	Carcinoma of floor of mouth	Left body and mental area	3	66.8	83.2	92
3	34	F	Sarcoma	Right ramus and body	2	86	93	96.5
4	25	M	Secondary defect	Right ramus and body	2	86.3	92	94.1
5	29	F	Sarcoma	Right ramus and body	3	91.9	95.9	98
6	26	F	Ameloblastoma	Right ramus and body	2 + 1 FBG	88.3	93.1	96.3
7	53	F	Keratocyst	Right body and mental area	2	54.7	66.4	74.4
8	48	F	Ameloblastoma	Left ramus and body	3 with double barrel	86.2	89.9	93
9	26	M	Ameloblastoma	Right body and mental area	2	80	90.6	95
10	50	F	Ameloblastoma	Right ramus and body	2	84.6	92	93.8
11	53	M	Secondary defect	Left ramus and body	2 + 1 FBG	78.6	87.1	91.6
12	22	M	Secondary defect	Right ramus and body	2 + 2 FBG	83.1	88.6	92.8
13	24	M	Secondary defect	Left ramus and body	3 + 2 FBG	73.6	80.8	87.1
14	50	F	Ameloblastoma	Left ramus and body	2 + 1 FBG	77.2	84.1	89.7
15	26	F	Ameloblastoma	Right ramus and body	3 + 1 FBG	76.8	83.7	91.2
16	23	M	Secondary defect	Right ramus and body	2 + 1 FBG	83	90.5	94.2
17	38	F	Ameloblastoma	Left ramus, body, and mental area	3	77.9	88	94.5
18	35	F	Sarcoma	Left body and mental area	2 + 2 FBG	68.6	85.8	93.9
19	43	M	Mucoepidermoid carcinoma	Right ramus and body	3	75.1	79.6	84.5
20	26	F	Ameloblastoma	Left ramus and body	3	78	83.9	87.5

F, female; M, male; FBG, non-vascularized free fibula bone graft.
[a] Total repeatability: within 1 mm 79.1 ± 8.6%; within 2 mm 87.1 ± 6.7%; within 3 mm 91.9 ± 5.4%.

readily. After mandibulectomy, the integrity of the mandible was disrupted and rotation of the remaining mandible may have occurred even though the remaining teeth were fixed by the dental splint.

Geometry dictates that the accurate location of three points on a three-dimensional object can determine the position of the object. In a study by Widmann et al.,[18] the mean navigation registration error was 0.49 ± 0.14 (range 0.37–0.9) mm in the edentulous jaw based on three fixed intraoral reference points. The total error of drillings was 0.88 ± 0.65 (range 0.0–4.24) mm. In the present study, three cylindrical-shaped objects were designed in the navigation plan as surface markers. These sites were identified with the aid of the tip of the navigation probe and replicated by drilling holes in the mandible before the osteotomy. These surface markers could be used to check the position of the residual mandible when the fibula bone was fixated.

The discrepancy between the preoperative design and actual surgical results is dependent upon different types of errors: technical, imaging, registration, application, and man-made. All errors are integrative and contribute to the accuracy. Registration is responsible for linking the virtual planning with the surgical site, and has been confirmed to be the most significant[18,19]. Hanasono and Skoracki found deviation of the fibula to be 4.11 ± 3.09 mm in mandibular reconstruction using rapid prototype modelling and a titanium plate pre-bending method[12]. In a cadaveric study of mandibular reconstruction in which preoperative planning was transferred via a template, mean translation of the fibula was 1.35 ± 0.86 mm.[1] In another study, the mean percentage overlap of the actual plate to the virtual plate was 58.73 ± 8.96%[20]. In the present study, satisfactory repeatability was achieved (91.9 ± 5.4% within 3 mm), demonstrating that surgical navigation was sufficiently reliable to implement the preoperative design for reconstruction of mandibular defects.

In conclusion, the present study showed that a surgical navigation method can be used to precisely implement a preoperative design for mandibular reconstruction using a vascularized free fibula flap. This navigation method can assist the surgical team in achieving good cosmetic and functional outcomes.

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Competing interests

The authors declare no conflict of interest.

Ethical approval

This research was approved by the institutional ethics committee of Peking University School and Hospital of Stomatology (PKUSSIRB-201310110).

Patient consent

Not required.

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