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Clinical Paper
TMJ Disorders

Application of a computer-assisted surgical navigation system in temporomandibular joint ankylosis surgery: a retrospective study

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Abstract. This retrospective study evaluated the effect of surgical computer-assisted navigation in temporomandibular joint (TMJ) ankylosis gap arthroplasty. Eighteen patients (25 sides) with bony ankylosis who underwent surgical treatment under computer-assisted navigation (navigation group) from May 2011 to April 2013 were assessed, along with 19 such patients (25 sides) treated without computer-assisted navigation (non-navigation group) from March 2009 to April 2011. The navigation group patients underwent surgery with the preservation of $\geq$3 mm bone thickness in the skull base and anterior wall of the external auditory canal. Postoperatively, computed tomography (CT) was used to measure the residual bone thickness in the skull base and anterior wall of the external auditory canal. Maximum mouth opening (MMO) changes were evaluated at >1 year of follow-up. Postoperative CT measurements showed that the lowest skull base thickness in the navigation group was significantly lower than that in the non-navigation group (3.86 ± 1.95 mm vs. 6.01 ± 3.07 mm, $P = 0.009$). The lowest thicknesses of the anterior wall of the external auditory canal were similar in the two groups. Postoperative follow-up showed similar average MMO in the two groups. Therefore, with the navigation system, TMJ ankylosis gap arthroplasty can achieve more extensive removal of the ankylosed bone, at least towards the skull base, under the premise of ensuring a safety distance of 3 mm.

Key words: computer-assisted navigation; temporomandibular joint ankylosis; skull base; anterior wall of the external auditory canal.

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Temporomandibular joint ankylosis (TMJ ankylosis) is a mandibular movement disorder that results from intra-articular fibrous or bony adhesion caused by lesions in the TMJ. It usually leads to secondary facial malformation, occlusal disorders, and sleep apnoea syndrome, seriously affecting physical function, body development, and the appearance of patients. The surgical treatment of TMJ ankylosis by joint gap arthroplasty was proposed by Humphry et al. in 1878.[1] In 1990, Kaban et al. proposed a treatment programme for TMJ ankylosis,[2] which was further improved in 2009.[3]

Regardless of the type of surgery selected, the first step in the surgical treatment of TMJ ankylosis is an extended resection of the ankylosed bone. Kaban et al. suggested that a bone gap of 1.5–2.5 cm should be preserved after completion of the osteotomy, because a too close bone section would result in new adhesions and consequently the recurrence of the ankylosis.[2,3] Others have advocated that a bone gap of 0.5–1.0 cm should be maintained, because a distance exceeding 1 cm would shorten the mandibular ramus height, causing a postoperative open bite and mandibular deviation.[4]

Although the ideal width of the osteotomy remains controversial, full removal of the bone adhesion is widely accepted by researchers to be a necessary condition for releasing the joint and reducing the recurrence of ankylosis. However, the removal of a sufficient amount of ankylosed bone is very difficult and highly risky. The anatomy of the TMJ region is very complex, with many important adjacent structures. In addition, bone adhesion makes the anatomical structure more ambiguous. The need to protect the surrounding structures also limits an adequate resection of the ankylosed bone, which may increase the risk of postoperative recurrence. Thus, how to achieve maximum removal of the ankylosed bone while ensuring safety constitutes a problem in the surgical treatment of the TMJ. Traditional treatment methods depend greatly on surgeon experience.

Computer-assisted navigation technologies are now used widely in the treatment of oral and maxillofacial diseases.[5–7] Assisted by a computer navigation system, one can achieve accurate real-time intraoperative positioning, and accurately transfer the preoperative design to the actual operation. This is undoubtedly highly suitable for intraoperative real-time positioning in TMJ ankylosis surgery, as it allows the relationships with the surrounding tissues to be seen. The application of surgical navigation systems in TMJ ankylosis surgery has been reported widely and is advocated for its usefulness in improving the safety and accuracy of the operation.[8–12] However, relevant large sample size studies are scarce. No data have been reported from studies assessing whether improvements are obtained postoperatively following the use of navigation surgery, in comparison with the traditional surgery.

This retrospective study evaluated the effect of computer-assisted navigation in TMJ ankylosis gap arthroplasty.

Materials and methods

Patients

A total of 18 patients with TMJ ankylosis, who underwent computer-assisted navigation surgery in the oral and maxillofacial trauma centre of the study institution from May 2011 to April 2013, were selected as the navigation group (group A). A further 19 such patients with TMJ ankylosis, who underwent surgery without the use of computer-assisted navigation from March 2009 to April 2011, were reviewed as the non-navigation group (group B). The two groups included 13 cases of bilateral TMJ ankylosis and 24 of unilateral TMJ ankylosis, giving a total of 50 affected sides (Fig. 1).

Inclusion criteria were the following: (1) sustained limitation of mouth opening lasting ≥8 weeks; (2) mouth opening ≤25 mm; (3) imaging examination showing damage to the TMJ structure, with osseous adhesion and Sawhney classification type II–IV ankylosis (type I: fibrous ankylosis; type II: osseous adhesion formed in the joint anterolaterally; type III: a wide range of osseous adhesion in the joint, but not exceeding the scope of the joint; type IV: ankylosed bone adhesion exceeding the range of the joint, with formation of extensive adhesion in the skull base, roots of the zygomatic arch, and ramus)[13,14]; (4) operations performed by the same surgeon; (5) patient re-examined by computed tomography (CT) within 2 weeks of the operation. This study was approved by the ethics committee of the study institution; all patients provided informed consent.

The 18 patients in group A (navigation group) included seven bilateral cases and 11 unilateral cases, for a total of 25 affected sides. This group comprised 10 males and eight females, with an average age of 28.6 years (range 9–62 years). By aetiology, there were two cases of inflammation, 10 of traffic accident injury, and six of falls, with a duration of between 12 and 320 months (average 85.3 months). Preoperative CT scans indicated six sides with Sawhney type II ankylosis, 10 with Sawhney type III, and nine with Sawhney type IV. Maximum preoperative mouth opening was 5.39 ± 5.59 mm (range 0–16 mm). Group A patients underwent computer-assisted navigation surgery.

The 19 patients in group B (non-navigation group) included six bilateral cases and 13 unilateral cases, amounting to a total of 25 affected sides. This group comprised 10 males and nine females, with an average age of 21.2 years (range 6–61 years). By aetiology, there were four cases of inflammation, 10 of traffic accident injury, and five of falls, with a duration of between 4 and 204 months (average 61.2 months). Preoperative CT scans revealed five sides with Sawhney type II ankylosis, 12 with Sawhney type III, and eight with Sawhney type IV. Maximum preoperative mouth opening was 7.89 ± 6.02 mm (range 1–20 mm). Group B patients all underwent traditional surgical treatment, rather than computer-assisted navigation surgery.

There was no significant difference between the two groups in age ($P = 0.146$) or preoperative maximum mouth opening ($P = 0.198$) (Table 1).

All patients were examined by spiral CT before and after the operation (helix with 0.625-mm slice thickness; Bright Speed 16, GE Healthcare, Buckinghamshire, UK). Preoperative CT data from the CT database were transferred to disc in DICOM format (Digital Imaging and Communications in Medicine). The CT data were then processed and transferred into iPlan CMF software (Brainlab AG, Feldkirchen, Germany), for preoperative surgical planning and postoperative evaluation. The VectorVision navigation system (Brainlab) was used for surgical navigation.

Operation method

Navigation group

Preoperative patient CT data were imported into the computer navigation system (VectorVision infrared navigation workstation) from a CD-ROM or U disc. After the induction of general anaesthesia, a reference frame with three light-reflecting balls was rigidly fixed to the patient's skull to identify his/her position. Registration was then completed through facial surface scanning using a Z-touch wireless laser pointer. The software automatically verified registration accuracy for all patients; the registration error was less than 1.5 mm in all cases.

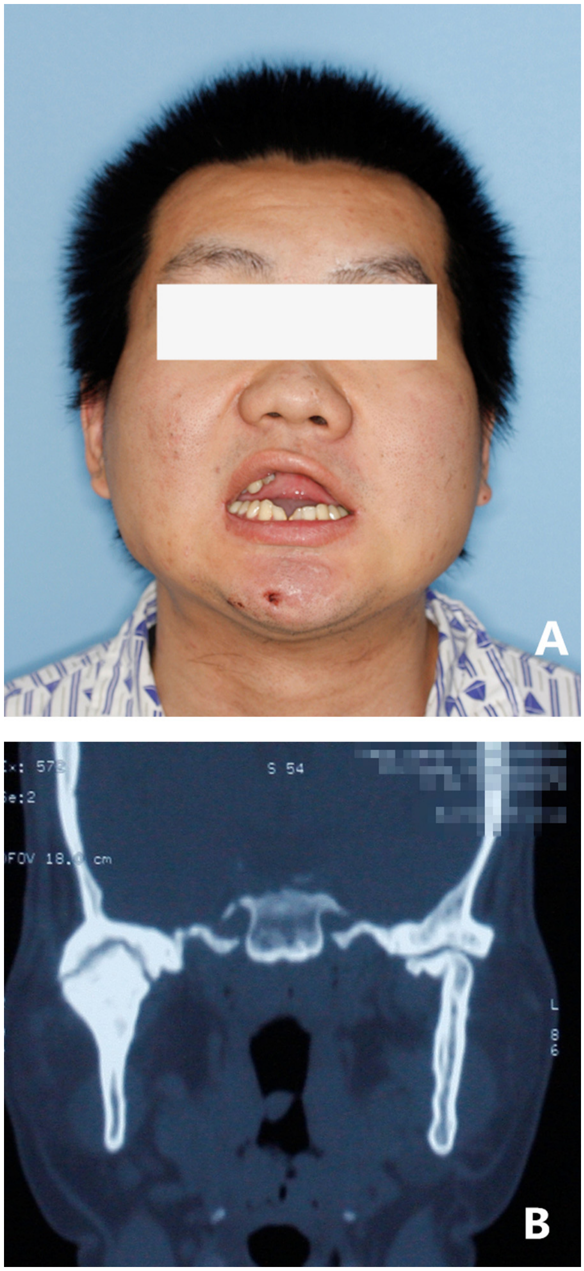

Fig. 1. The case of a man who had suffered bilateral condyle fractures as a result of falling from a height 1 year previously. The patient underwent conservative treatment and mouth opening exercises at a local hospital, but gradually became unable to open his mouth. (A) Maximum mouth opening was only 8 mm before the operation. (B) Coronal section CT image showing extensive bony adhesion in the right TMJ before the operation.

A pre-auricular incision was applied to expose the TMJ region. Then, a fissure drill was used to perform the osteotomy, cutting and removing the ankylosed bone in big pieces. To render the procedure safe, the navigation system was used to indicate the distance between the actual position of the operation and the medial border of the ankylosed bone.

After completion of the osteotomy and TMJ release, a round bur was used to remove the ankylosed bone at the upper bone surface and to carefully shape the glenoid fossa. During this step, the distance from the top of the glenoid fossa to the skull base of the medial cranial fossa and that from the posterior margin of the fossa to the anterior border of the bony external auditory canal was monitored via the navigation system (Figs. 2 and 3). The 'tooltip' function in the navigation software was used to display the safety distance, with an additional instruction for a 3-mm distance along the probe direction in the real-time position of the navigation probe (Figs. 2B and 3B). After shaping the glenoid fossa, at least 3 mm of bone thickness was maintained at the skull base and anterior wall of the bony external auditory canal. Finally, a 10–20-mm bone gap was eventually formed from the top of the glenoid fossa to the residual condyle or mandibular ramus. After gap arthroplasty of one or two sides, depending on the patient's situation, the passive maximum mouth opening distance was checked. If this did not reach 35 mm, arthroplasty of the other side or resection of the coronoid process was done until more than 35 mm of passive maximum mouth opening was obtained.

Several procedures were selected and applied to reconstruct the condyle, according to the extent of the bone defect: (1) autologous bone grafting with costal cartilage, coronoid process, or iliac crest bone; (2) L-shaped osteotomy of the mandibular ramus and distraction osteogenesis (DO); (3) artificial joint replacement. If the articular disc was found to be displaced during the operation, it was reduced. If not, a temporal musculo-fascial flap was used

Table 1. Comparisons between the navigation group and non-navigation group.

	Navigation group	Non-navigation group	*P*-value
Age, years	28.61 ± 15.91	21.21 ± 14.21	0.146
Preoperative maximum mouth opening (mm)	5.39 ± 5.59	7.89 ± 6.02	0.198
Postoperative measurements			
Thickness of the skull base (mm)	3.86 ± 1.95	6.01 ± 3.07	0.009[a]
Thickness of the anterior wall of the external auditory canal (mm)	3.43 ± 2.40	4.26 ± 2.78	0.377
Maximum mouth opening (mm)	36.39 ± 7.36	32.47 ± 13.16	0.976
Ankylosis recurrence rate	5.6% (1/18)	21.1% (4/19)	

[a] Significant at $P < 0.05$.

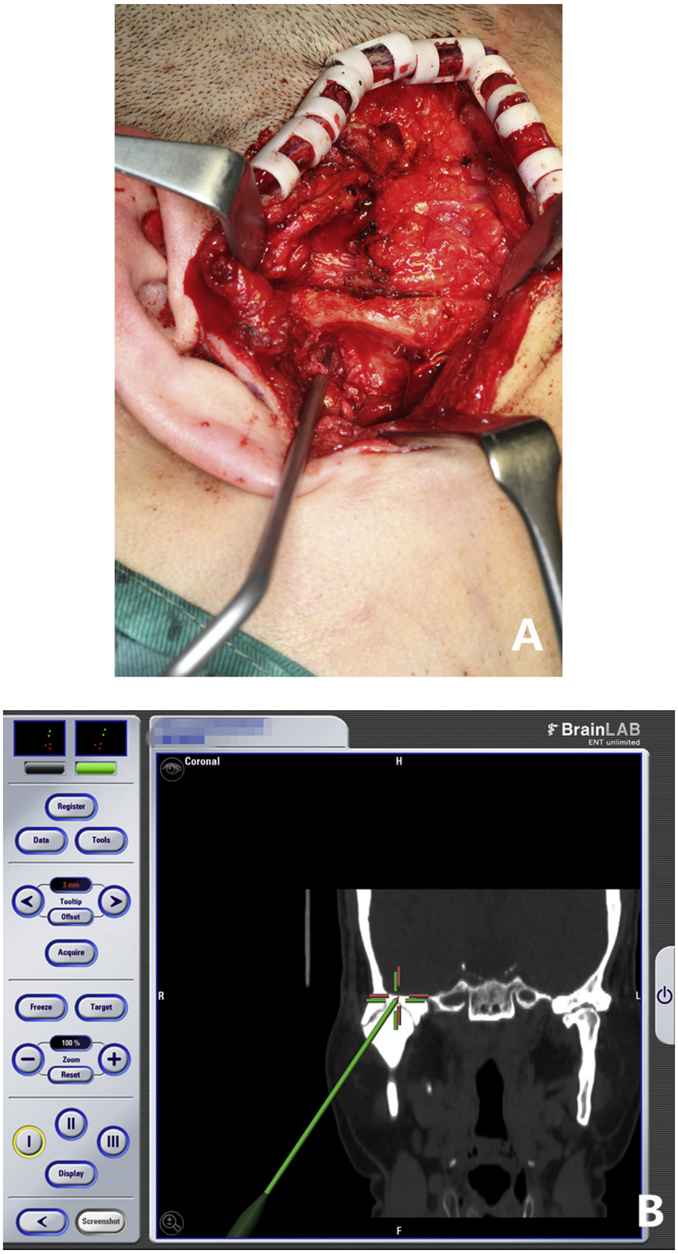

Fig. 2. The surgical navigation system was used to maintain a safety distance from the middle cranial fossa of at least 3 mm. (A) After osteotomy, the top of the glenoid fossa was detected with the navigation probe to determine the distance between the position of the operation and the middle cranial fossa. (B) During surgery, the detected position was shown on the screen of the navigation workstation with a green arrow. As an additional instruction, the position 3 mm distant (along the direction of the probe) in the real-time position of the navigation probe was shown in red; this was achieved using the 'tooltip' function. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

to reconstruct the soft tissue separation between the glenoid fossa and condylar process. Finally, the wound was closed to complete the procedure.

Non-navigation group

In the non-navigation group, the computer-assisted navigation system was not used during surgery, but the remaining procedures and methods were the same as those described above for the navigation group. The safety of the procedure and extent of removal of the ankylosed bone just relied on the surgeon's experience. All of the surgeries were performed by the same surgeon who had about 30 years of experience in the surgical treatment of TMJ ankylosis. Usually the central part of the ankylosed bone was identified through observing the preoperative CT scan, and then the ankylosed bone was removed in small pieces. After completion of the osteotomy and TMJ release, a round bur was used to remove the ankylosed bone at the upper bone surface and to carefully shape the glenoid fossa.

Postoperative CT measurements and statistical analysis

The patients were re-examined by spiral CT within 2 weeks after the operation. The postoperative CT measurements of the affected sides were used to evaluate and compare the effects of bone removal in the two treatment groups, including the lowest thicknesses of the skull base and anterior wall of the external auditory canal. All postoperative measurements were performed by an oral and maxillofacial doctor who was blinded to the grouping and patient personal information, and was familiar with the manipulation of the software and measurement.

The measurements were performed as follows: (1) postoperative CT data were imported into the surgical planning software iPlan CMF 3.0 (Brainlab) and adjusted to the bone window. The patient's midsagittal, coronal, and Frankfort horizontal planes were adjusted to coincide with the 3D reference planes of the software system. (2) Measurements were made of the lowest thickness of the skull base (Fig. 4A): in the coronal window, five continuous slices were selected that showed the maximum inner and outer diameters of residual or reconstructed condyle. The shortest distance from the upper bound of the glenoid fossa to the medial cranial cavity was measured in each slice as the lowest thickness of the skull base; the five values were recorded and averaged, to 0.01 mm accuracy. (3) Measurements were made of the lowest thickness of the anterior wall of the external auditory canal (Fig. 4B): in the sagittal window, five continuous slices were selected that showed the maximum anterior and posterior diameters of the residual or reconstructed condyle. The shortest distance from the posterior bound of the affected glenoid fossa to the bony external auditory canal was measured in each slice as the lowest thickness of the anterior wall of the external auditory canal; the five values were recorded and averaged, to 0.01 mm accuracy.

Average measurement data of the lowest thickness of the skull base and anterior wall of the external auditory canal in both groups were analyzed using SPSS for

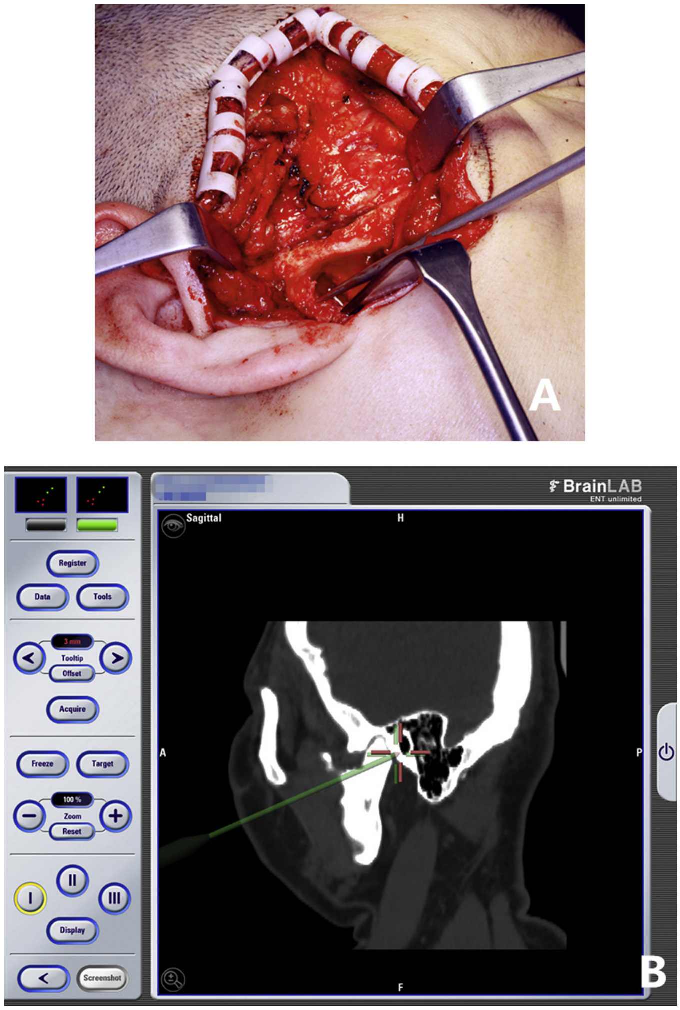

Fig. 3. The surgical navigation system was used to maintain a safety distance from the bony external auditory canal of at least 3 mm. (A) After osteotomy, the posterior border of the glenoid fossa was detected with the navigation probe to determine the distance from the position of the operation to the bony external auditory canal. (B) During surgery, the detected position was shown on the screen of the navigation workstation with a green arrow. As an additional instruction, the position 3 mm distant (along the direction of the probe) in the real-time position of the navigation probe was shown in red; this was achieved using the 'tooltip' function. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

Windows version 13.0 software (SPSS Inc., Chicago, IL, USA). Data were assessed by non-parametric Wilcoxon test. $P < 0.05$ was considered statistically significant.

Clinical follow-up after surgery

Patients who underwent condyle reconstruction with an autologous bone graft or artificial joint were required to perform mouth opening exercises over a period of 3 months, starting at 1 week after surgery. For patients who underwent DO, moderate mouth opening exercises were performed starting after the completion of traction, until the traction devices were removed in a second operation.

All patients were followed up for more than 1 year to review mandibular movement and changes in maximum mouth opening (Fig. 5).

Results

All 37 patients in the two groups underwent surgical treatment without any significant complications. In the navigation group (18 patients), surgery was performed on 25 ankylosed joints. Condyle reconstruction was performed for 22 of these joints: 13 through DO, six with a coracoid transplantation, one with a rib graft, and two with an artificial joint replacement. In the non-navigation group (19 patients), surgery was performed on 25 ankylosed joints. Eighteen joints underwent condyle reconstruction: six with DO, six with a coracoid transplantation, three with a rib graft, and three with an artificial joint replacement.

Postoperative CT measurements were recorded for both groups, with 25 ankylosed joints each. The lowest thickness of the skull base was 3.86 ± 1.95 mm in the navigation group (group A) and 6.01 ± 3.07 mm in the non-navigation group (group B); the difference between the two groups was significant ($P = 0.009$, Table 1). Meanwhile, the lowest thickness of the anterior wall of the external auditory canal was 3.43 ± 2.40 mm in the navigation group and 4.26 ± 2.78 mm in the non-navigation group, with no significant difference between the two groups ($P = 0.377$, Table 1).

Follow-up for all patients ranged from 1 to 5 years. Maximum mouth opening at the latest follow-up was 36.39 ± 7.36 mm (range 10–47 mm) for the navigation group, with 15 patients (83.3%, 15/18) showing values above 35 mm; one patient (5.6%, 1/18) showed a value of only 10 mm after 3 years, and recurrence of the ankylosis was found on CT examination. Maximum mouth opening at the latest follow-up in the non-navigation group was 32.47 ± 13.16 mm (range 5–44 mm), including 14 patients (73.7%, 14/19) with values exceeding 35 mm; four patients (21.1%, 4/19) showed values below 15 mm (range 5–15 mm), with recurrence of the ankylosis seen on CT examination. There was no significant difference in the degree of maximum mouth opening at the latest follow-up between the two groups ($P = 0.976$).

Discussion

Computer-assisted surgical navigation systems have been applied in the treatment of oral and maxillofacial diseases for 20 years.[5–7] The intraoperative real-time display of the operation position and its relationship with the surrounding structures can significantly increase the accuracy of the operation and reduce the risks, especially for high-risk operations such as gap arthroplasty for TMJ ankylosis. Schmelzeisen et al. first applied this navigation system to TMJ ankylosis surgery in 2002, and found that it significantly improved the safety of the operation and reduced the incidence of complications.[8] In 2007, Malis et al. used a navigation system to perform an individualized total joint replacement for a patient with bilateral TMJ ankylosis.[9] Yu et al. reported four cases of unilateral TMJ ankylosis

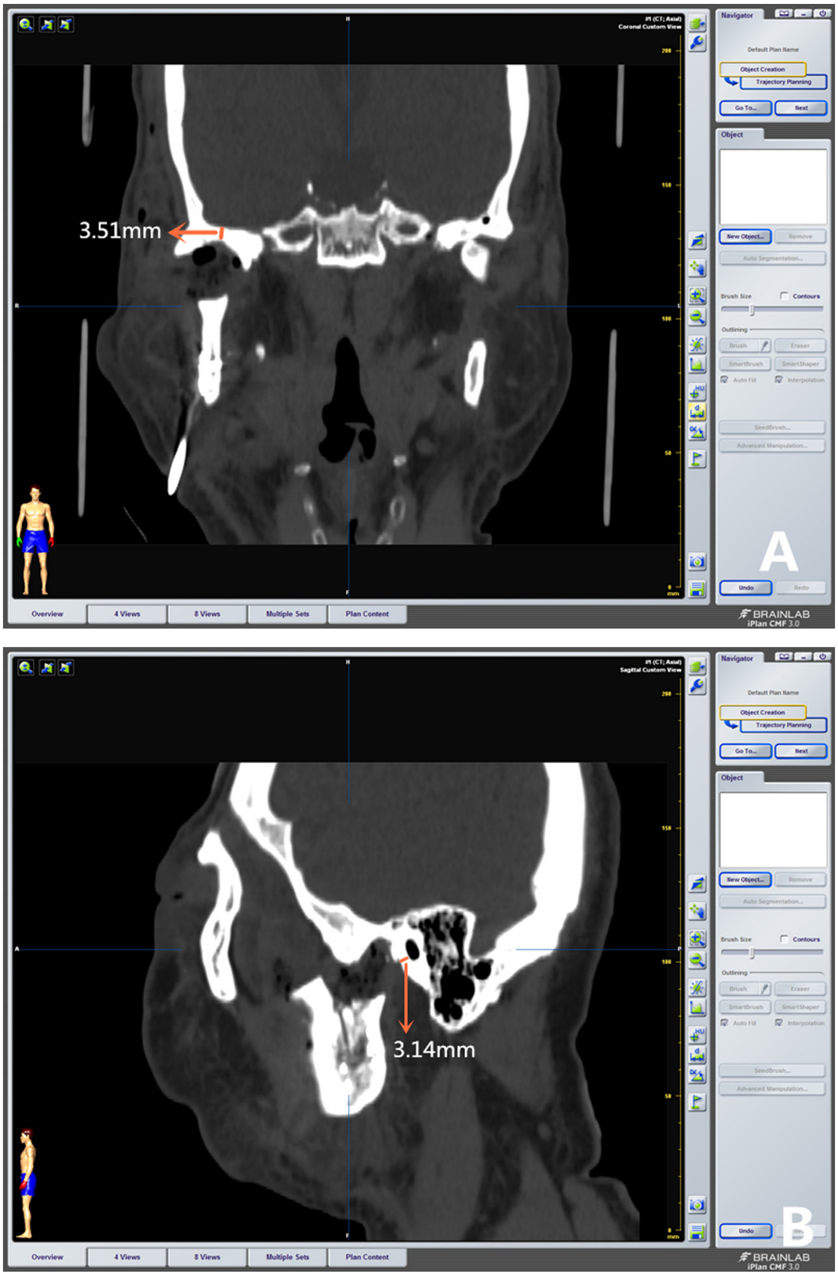

Fig. 4. CT measurements of the patient at 1 week after the operation. (A) The lowest thickness of the skull base was measured on coronal section CT images; this was 3.51 mm (indicated with the red arrow). (B) The lowest thickness of the anterior wall of the bony external auditory canal was measured on sagittal section CT images; this was 3.14 mm (indicated with the red arrow). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

surgery assisted by a computer navigation system, with good postoperative results.[10] No damage to the adjacent structures or complications were reported, and no significant difference was found between the residual thickness of the bone in the skull base of the affected side and the uninjured side, which demonstrated the advantages of the navigation system in improving the safety and precision of the operation. These previous studies were based on the application of navigation in individual cases, with no comparison with conventional non-navigation surgery.

With regard to the design of the navigation surgery for unilateral TMJ ankylosis, Yu et al. mirrored the skull base of the unaffected side to the affected one in order to guide the osteotomy location, and observed the relationship between the real surgical site and the middle cranial fossa as well as the external auditory canal, thereby avoiding the occurrence of perforation.[10] Postoperative CT showed the morphology of the glenoid fossa to match that designed preoperatively well, with complete removal of the ankylosed bone. However, this method is not suitable for bilateral TMJ ankylosis.

The present authors believe that two main points should be taken into account when designing the navigation for TMJ ankylosis: the first is the maximum range of resection of the ankylosed bone, and the other is the safety distance from the surgical site to the middle cranial fossa and bony external auditory canal. Osteotomy and removal of the ankylosed bone on the mandibular ramus can be observed directly during the operation. Therefore, the surgical navigation system should be focused on helping to maintain a safe distance from middle cranial fossa and bony external auditory canal. This is not only applicable in unilateral TMJ ankylosis, but also in bilateral TMJ ankylosis.

Schmelzeisen et al.,[8] Yu et al.,[10] and others[9,12] have also suggested maintaining a safety distance of 2–3 mm to the skull base and external auditory canal. Nevertheless, this safety distance remains uncharacterized. Multiple studies have measured the average lowest thickness of the glenoid fossa in normal TMJs, and have reported measurements in the range of 0.7–1.22 mm.[15–19] The average thickness of the anterior wall of the bony external auditory canal measured by Greene et al. was 1.5 mm.[20] Considering that the surface registration method of the surgical navigation system may be subject to a systematic error of about 1.5 mm, a safety distance of 3 mm to the middle cranial fossa and bony external auditory canal was kept in the present study, to ensure the safety of the operation.

Through CT measurements, a significant difference was found in lowest thickness of the skull base between the navigation group (3.86 ± 1.95 mm) and non-navigation group (6.01 ± 3.07 mm) ($P = 0.009$). Meanwhile, there was no statistically significant difference in lowest thickness of the anterior wall of the external auditory canal between the two groups ($P = 0.377$). Through pre-auricular approach, the medial-posterior part of the ankylosed bone could usually be exposed very well, and it was beneficial for the resection of ankylosed bone. CT measurements of both the skull base and anterior wall of the external auditory canal in the navigation group were closer to 3 mm than the non-navigation group values, without perforation of the skull base or external auditory canal. This demonstrated that the

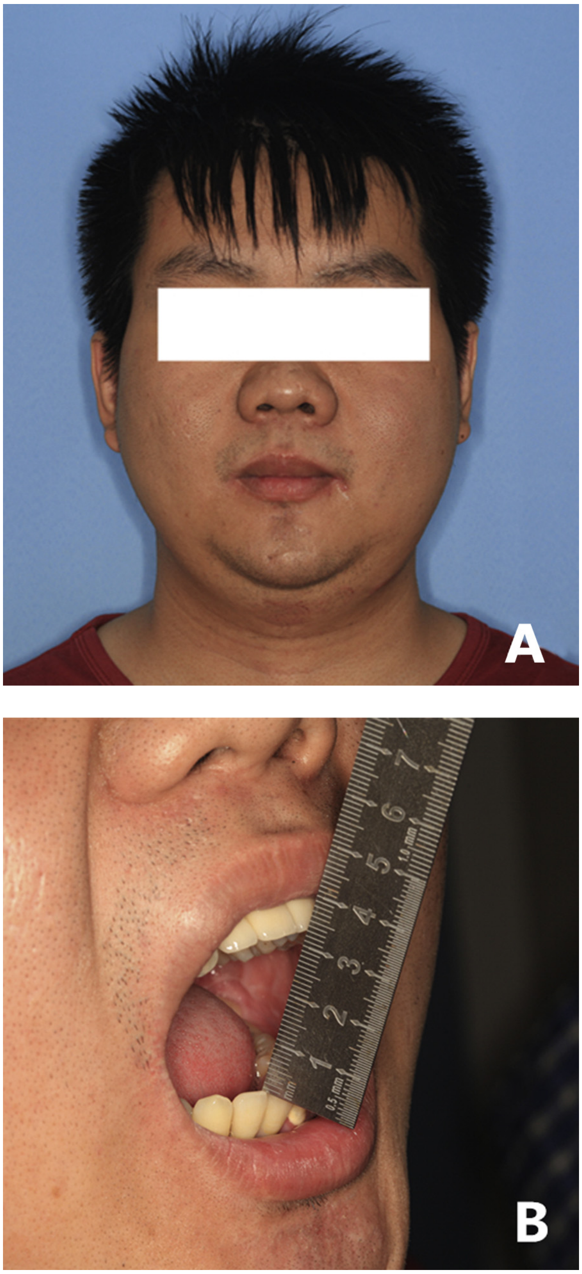

Fig. 5. At the 2-year follow-up – after TMJ gap arthroplasty, distraction osteogenesis for condyle reconstruction, and the provision of implant-supported prostheses – the patient was able to open his mouth up to 33 mm. (A) Front view of the patient at follow-up. (B) Measurement of the degree of maximum mouth opening.

joint ankylosis operation could achieve more extensive removal of ankylosed bone in the navigation group, at least in the direction of the skull base, under the premise of ensuring a safety distance.

On the other hand, the data distribution in the navigation group was more concentrated than that obtained for the non-navigation group. Indeed, the statistical analysis yielded reduced standard deviations in the navigation group compared with the non-navigation group, suggesting that the non-navigation group data had a larger discrete degree (Fig. 6). The remaining bone thickness following ankylosis surgery assisted by navigation was relatively stable, with relatively good controllability and repeatability. Meanwhile, for traditional surgery without navigation, it was difficult to control the amount of bone removed, and individual differences in remaining bone thickness were larger, resulting in poor reproducibility.

Postoperative follow-up showed no significant difference in maximum mouth opening between the navigation (36.39 ± 7.36 mm) and non-navigation (32.47 ± 13.16 mm) groups. There was one patient with ankylosis recurrence in the navigation group and four such patients in the non-navigation group; the ankylosis recurrence rate in the navigation group (5.6%, 1/18) was lower than that in the non-navigation group (21.1%, 4/19). However, many factors can influence the improvement in mouth opening after TMJ ankylosis surgery and the ankylosis recurrence rate, including the severity of the ankylosis, the method of TMJ reconstruction, the duration of postoperative mouth opening exercises, and the length of follow-up. Thus, the overall influence of computer-assisted navigation surgery on the effect of TMJ ankylosis treatment could not be evaluated accurately.

In this study, there seems to be no significant difference for the outcome between the two groups, but it does not suggest that the navigation system does not help. All of the surgeries in the two groups of patients were performed by the same surgeon who has about 30 years of experience in the surgical treatment of TMJ ankylosis. His extensive clinical experience was very helpful in preventing postoperative complications. Even then, the postoperative measurements demonstrated that the navigation system was helpful to this surgeon in increasing the amount of bone removal on the top of the TMJ glenoid fossa and improving the stability. This is also of relevance for surgeons who have less experience in the surgical treatment of TMJ ankylosis, for example, young doctors. In non-navigation surgery, the relationship between the surgical location and the surrounding anatomical structures during bone removal can only be judged by careful observation, while with navigation surgery, the relationship is displayed in real time, which will significantly reduce the difficulty of the operation and lower the risk of complications. With the assistance of the navigation system, the surgical treatment of TMJ ankylosis could have a larger scope and could be performed by surgeons who have not amassed a great deal of experience. Nowadays, all gap arthroplasty surgeries for TMJ ankylosis in the authors' department are performed with the assistance of the navigation system.

In conclusion, when using gap arthroplasty for the treatment of TMJ ankylosis, a safety distance of at least 3 mm from the middle cranial fossa and bony external auditory canal should be maintained to avoid injury. In addition, the application

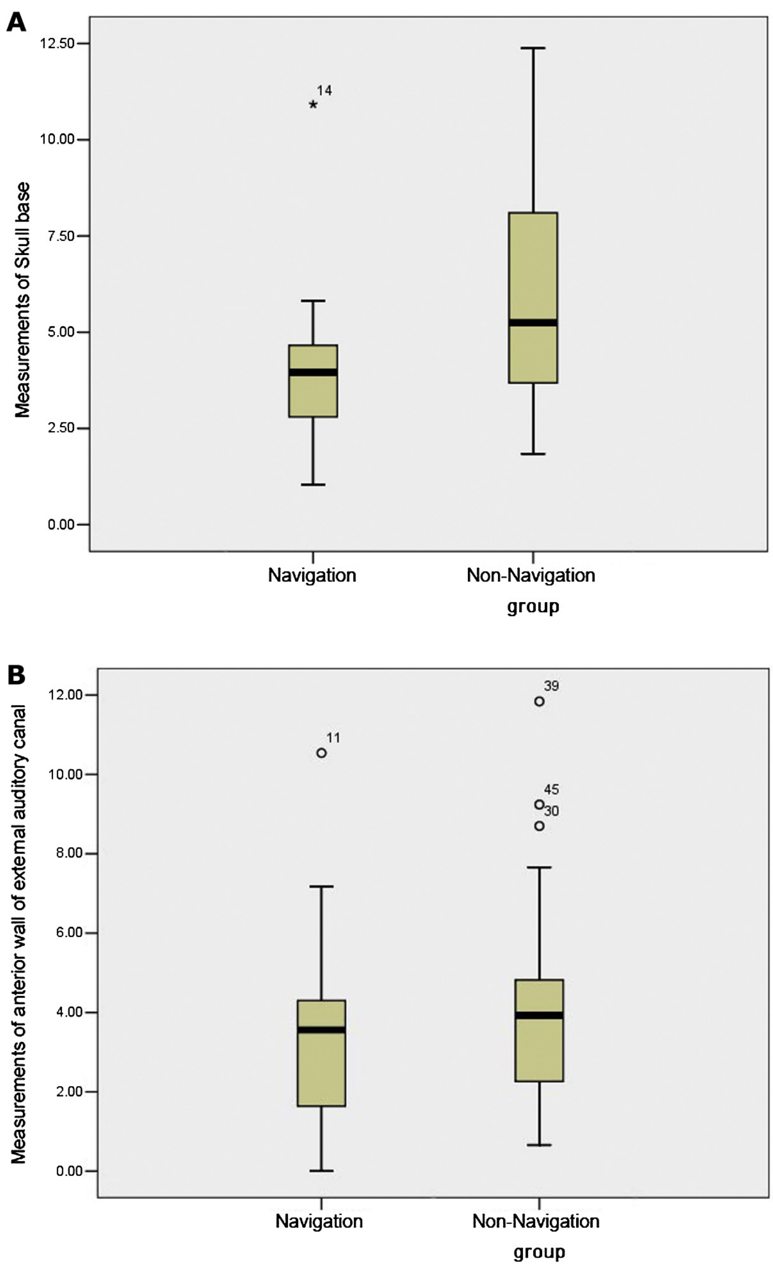

Fig. 6. Distribution of the CT measurement data in the two study groups (navigation group and non-navigation group): (A) the lowest thickness of the skull base; (B) the lowest thickness of the anterior wall of the bony external auditory canal.

of a computer-assisted navigation system can help the surgeon to achieve more extensive removal of the ankylosed bone, at least in the direction of the skull base, under the premise of ensuring a safety distance.

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Competing interests

None.

Ethical approval

This study was approved by the institutional ethics committee (ethics approval document No. PKUSSIRB-201416095).

Patient consent

All patients or their legal guardians provided signed informed consent for publication of the images.

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