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Original Article

A new concept for mandible reconstruction after oncological resection: Multisegment virtual surgical planning

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ABSTRACT

Purpose: Virtual surgical planning (VSP) is good for three dimensional reconstructions in maxillofacial surgery, but it is not problem-free completely especially when the resection margins cannot be affirmed in preoperative period. We aimed to obtain an ideal reconstruction with elaborating VSP to be prepared for adverse conditions during surgery and to proceed the oncological resections step- by- step with A, B, and C resection planes.

Patients and methods: Four patients undergoing multisegment VSP for the primary mandible malignancies were included in the study. The first resection margin was detected as plan A in VSP, and plans of B and C were also prepared considering the tumor- positive result of intraoperative frozen section procedure.

Results: Following the tumor resection, margins were extended to the plan B in two patients, and plan C in one patient in accordance with the results of the frozen section procedure.Histogram comparison of the localizations of osteotomies in mandible and fibula, and positions of the implants were calculated at a confidence level of 95 % ($p > 0.95$) and mean difference was found -0.55 mm, while standard deviation was 1.76 mm.

Conclusion: Multisegment virtual surgical planning seems to achieve the optimal reconstruction with the staged resection preventing redundant removal of tumor- free structures like bone and teeth.

1. Introduction

Attaining the ideal mandible reconstruction once the integrity is disrupted by segmental resections for head and neck tumors is challenging. Mandible is the only mobile joint of the craniofacial region and one of the most forcible joints of human body. It is also one of the main components of the occlusion. Therefore, mandibular reconstruction must constitute both the precise tridimensional integrity to bring in the perfect occlusion with perfect TMJ function and structural stability in integrity to withstand the masticatory forces.

Free fibula flap has been applied as a standard reconstructive option over the years following the composite resection of mandible however inset of the bony flap in such a complex anatomy has become the focus of many researchers [1,2].

It is well known that three-dimensional virtual surgical planning (VSP) which is widely used in maxillofacial surgery has also been efficiently applied in mandible reconstruction [3,4]. The segments of mandible to resect and to replace, length and directions of the plate and screws can be determined before the surgery owing to VSP. Although concept of VSP shortens the operative time and makes it easier, this is true only the preoperative planning is done properly. In other words, even a minimal error in planning may lead to failure of whole surgical plan since VSP concept leaves no space for intraoperative operative flexibility.

This disadvantage of VSP, namely limited surgical adaptability, is the main restriction of application of VSP in oncological resections, where achieving the tumor-free surgical margins has utmost importance in the surgical course.

To achieve the adequate margins in VSP, resection borders can be determined as far away the mandible mass as possible according to the surgeon's experience. However standard VSP may still be inadequate in cases of (1) multifocal and multicentric tumors; (2) satellite lesions that cannot be diagnosed as malignancy in the preoperative period; (3) and most importantly the conditions that we do not prefer to sacrifice tumor- free mandible segments and teeth.

We developed a new approach elaborating VSP to be prepared for adverse conditions during surgery and to proceed the oncological resections step by step with A, B, and C resection planes. In this study, we aimed to investigate the applicability and results of multisegment VSP which contained the first, second and third resection plans, fibula cutting guides accordingly, and the patient specific implant.

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2. Patients and methods

2.1. Patients

Four patients undergoing multisegment VSP for the primary mandible malignancies were included in the study. DICOM (Digital Imaging and Communications in Medicine) data were obtained from three dimensional craniomaxillofacial and lower extremity high resolution CT (computed tomography) scans of the patients preoperatively. Additionally, CT angiography of both lower extremities was also provided not to miss the peroneal artery dominancy. The patients undergoing the surgery of oncological resection and reconstruction with free fibula flap following the multisegment VSP were regularly followed-up. Control craniomaxillofacial CT scan was performed 3 months postoperatively and the superposition to surgical planning was assessed. Overlapping of osteotomy localizations in mandible and fibula, and plate compatibility in determined points were evaluated through histogram analysis. Written consent forms were obtained from the patients and study was conducted according to the principles in the Declaration of Helsinki. Ethical approval was given to the study by institutional ethical committee (ethical registration number: 3/2022.K-80). Demographic data (age, sex), histological type of tumor, preferred resection plane in the operation (A, B, and C), number of fibula osteotomies, interincisal opening distance (mm), and complications were recorded.

2.2. Multisegment VSP and surgical technique

A high-resolution CT scan of the patient's craniofacial skeleton and fibula were obtained prior to surgery using a multi-detector CT scanner, (Somatom Definition, Siemens, Erlangen, Germany). The acquired DICOM-format data were then converted into 3-dimensional models of the maxillofacial skeleton utilizing both automatic and manual segmentation techniques on the Mimics Innovation Suite software (Materialise NV, Leuven, Belgium) (Fig. 1). Thereafter, a virtual surgery planning session was held between the surgeon (senior author) and the service providers responsible for design and manufacturing of the implants and cutting guides.

Initially, a 1 cm long distance (2 cm in the case with osteosarcoma) from the both sides of tumor margins was marked on the mandible model and the first resection plane was assigned as plan A (Fig. 2a). Plans of B and C were prepared for further resections in case of tumor positive surgical margins after intraoperative frozen section procedure (Fig. 2b). The distances between the resection planes (between A and B, and C and B) in the both sides were calculated to be approximately 2 cm. Afterwards, the sections of fibula planned to be cut from both distally and proximally were marked. Triangular bone segments were also designated to be removed according to plans of A, B, and C to obtain proper angles of neomandible. Directions of the fibula cutting planes were overlapped with the directions of resection planes to design the accurate cutting guides (Fig. 2b). Care was taken not to damage teeth roots while planning of the directions. Patient specific implants were designated to be compatible with all of three plans to enable the fixation of bone segments, respectively.

One of the surgical teams performed the oncological resection and preparation of recipient vessels, whereas the other team harvested the free fibula flap. The vascular connection of fibula flap was left intact until the tumor margins were confirmed by pathologists. Further resections were proceeded to the plans of B and C in case of tumor- positive margins. Superior thyroid artery was used as a donor artery in all cases. Concomitant vein and external jugular vein were the two veins used for end-to-end anastomoses with peroneal veins. After the fibula flap was separated from its vascular connection shaping of the bone was performed on mayo stand and patient specific implant was fixed on it by screws. Then, it was attached with the remained mandible in the recipient site, and appropriate anastomoses were done. Mostly, a skin paddle of the flap adapted to the floor of mouth was also used for flap monitoring. During the flap inset and anastomoses of vessels the second surgical team repaired the donor area; thus, operation time was shortened obviously.

2.3. Cutting guides

Firstly, cutting guides for resection plans of A, B, and C were created. All of three cutting planes for each side were included in one guide; therefore, following the first resection cutting guide was not removed until the tumor margins were confirmed. Otherwise, to reinsert of the cutting guide after the first resection could be misleading. The distance was a 1 cm long from each side of the tumor margins for the first cutting plane (2 cm in the case with osteosarcoma), whereas it was 2 cm for the following cutting planes (Fig. 3). Care was taken not to injury teeth roots while designating the directions of cut. Afterwards, fibula was superposed with the mandible to determine the osteotomy lines, directions and angles on the fibula as well. Adding the wedge excision areas, it was considered not to leave the bone segment less than 1,5 cm.

2.4. Design of patient-specific implant

During the meeting the parameters of implant such as thickness, position and directions of the screw holes were confirmed. The main priority was to design the implant with the same contour of lower outer line of original mandible (Fig. 4). With the design of three-

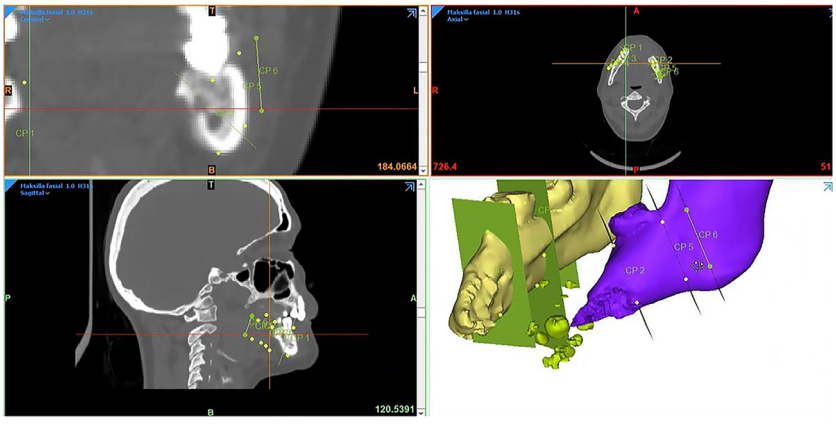

Fig. 1. DICOM-format data were converted into 3-dimensional models of the maxillofacial skeleton utilizing both automatic and manual segmentation techniques on the Mimics Innovation Suite software (*Materialise NV, Leuven, Belgium*) and resection plans were created considering the directions of teeth roots.

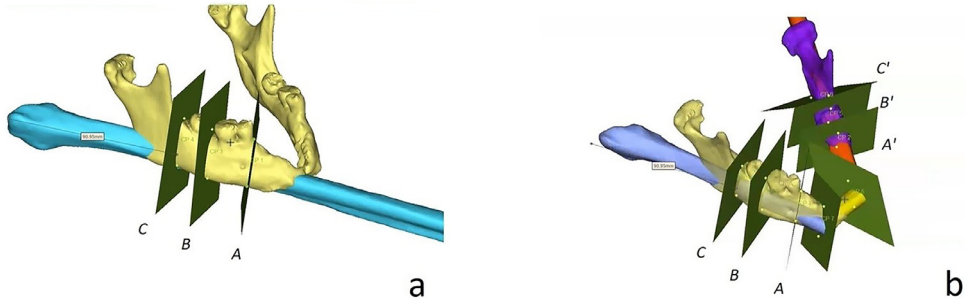

Fig. 2. *a*- Overlapping of the mandibular resection planes with the fibula; *b*- fibula was oriented to create the new symphysis.

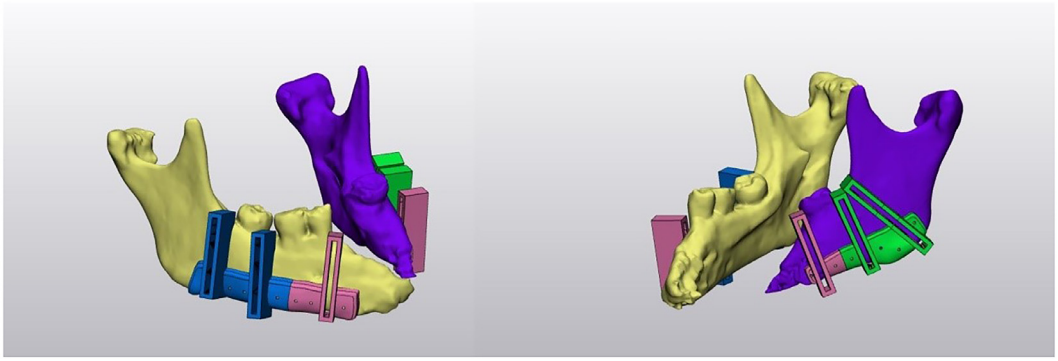

Fig. 3. Cutting guides for the both sides were designated in the VSP to be fixed to the mandible (*VSP: virtual surgical planning*).

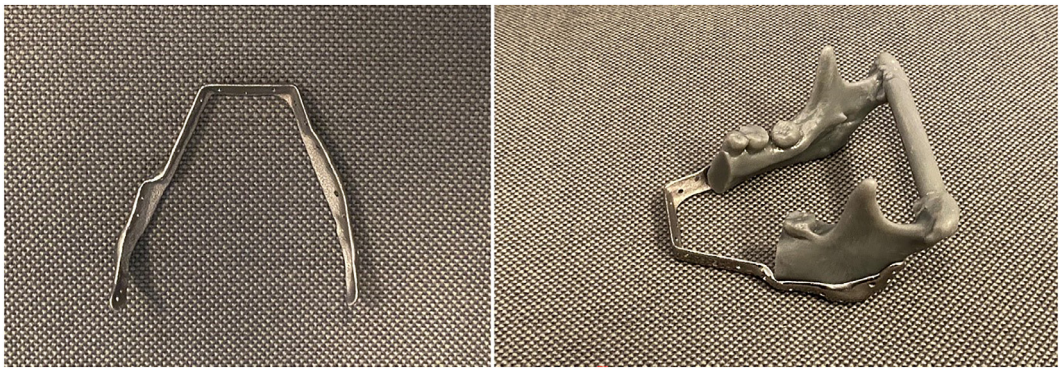

Fig. 4. A view of the titanium implant which was compatible with the three resection plans resembling the outer contour of original mandible. The floor of implant was designated to be curved to hold the lower margin of mandible and fibula segments.

dimensional shape of implant the problem of resembling the outer contour of original mandible via only fibula bones was overcome. The floor of implant was designated to be curved to hold the lower margin of mandible and fibula segments (Figs. 4 and 5). This concept provided to cling to the remaining parts of mandible accurately no matter which resection plan was performed. Additionally, the length of screws and the relationships with the teeth roots were also calculated.

3. Results

A total of 4 multisegment VSP of 4 patients were included in the study. The mean age of the patients was 49.5 (Table 1). The ratio of female to male was 1:3. Histopathological diagnosis was mandibular osteosarcoma in one patient, whereas it was squamous cell carcinoma in the remaining cases. Because one of the patients did not come to the surgery after the virtual surgical planning, the intraoperative and postoperative data were not acquired. Another patient (number 4 in Table 1), the margins of whom were confirmed to be continued in skull base intraoperatively, did not undergo the free fibula flap but only patient- specific implant manufactured according to the VSP was placed. The reconstruction with free fibula flap based on the VSP was performed to the remaining two patients.

Following the tumor resection, margins were extended to the plan B in two patients, and plan C in one patient in compliance with the results of the frozen section procedure. Accordingly, four osteotomies were done in one patient, while five osteotomies were performed in another one. No flap loss and complications were recorded but the donor area dehiscence in one patient. The mean distance of interincisal opening was 45 mm in the postoperative 3 months period. Malocclusion was not encountered in any of the patients postoperatively.

Postoperative 3 months maxillofacial CT scans of the patients were compared with the VSP and differences were noted (Fig. 6). The values of the points randomly chosen on the three-dimensional models of implant and bony tissue were determined. The differences between the points of VSP and postoperative CT model were calculated in millimeters in three-dimensional coordinate system. Histogram comparison of the localizations of osteotomies in mandible and fibula, and positions of the implants were calculated at a confidence

Fig. 5. *a*- A fibula cutting guide was placed and fibula was cut from the appropriate parts both proximally and distally; *b*- after fixation of the cutting guide fibula was cut from the determined planes; *c*- after osteotomies fibula was designated to be fixed to the patient specific implant on the mayo table; *d*- a final view of the free fibula flap after fixation to the remaining mandible.

level of 95 % ($p > 0.95$) and mean difference was found -0.55 mm; while standard deviation was 1.76 mm (Figs. 6 and 7).

4. Discussion

Over the past 15 years, reconstructive modelling has promoted craniomaxillofacial surgery with the improvement in virtual surgical planning, computer-aided design (CAD) and computer-aided manufacturing (CAM). In the literature, there are several studies demonstrating the application of virtual surgical planning in plastic surgery and maxillofacial surgery [5–10]. Though the usage of novel technological equipment in the surgery is common, general surgical principles should not be thrown out of focus. Therefore, the virtual surgical planning contains almost the same components and steps in craniomaxillofacial surgery; however, orthognathic surgery, maxillofacial fractures and defects, and oncological maxillofacial reconstruction should be approached as different concepts. Especially in the oncological surgeries, it must be considered that surgical planning can change intraoperatively, thus it cannot always be possible to stay the course. In their study, Roser et al. investigated the accuracy of jaw reconstruction with the free fibula flap comparing the final results with the preoperative virtual surgical planning [11]. And they mentioned that it seems necessary to add one resection plan both distally and proximally in the oncological reconstructions, however the most challenging part of this approach is to prepare one implant compatible with all the resection plans. The applicability of multisegment VSP was ensured after designing the patient-specific implant in the same shape with mandibular contour, which was the only option to obtain an ideal reconstruction in all resections plans with one implant. In this study, we applied a novel approach of VSP to four patients and designated the planning of multisegment resection and reconstructive procedures before the surgery, respectively.

In two of four patients we had to exceed the resection to the following plans because of the tumor- positive surgical margins. In 2018, Smith et al. evaluated the surgical margins of 127 patients who underwent the segmental mandibulectomy due to oral squamous cell carcinoma and bony resection margins were found positive in 21 % of the patients [12]. In addition, it was mentioned that 5-year survival rate of this group was significantly less than the others ($p < 0.005$) and exceeding of surgical margins is necessary if tumor-

Table 1
The characteristic features of the patients.

Patients	Age/ Gender	Histopathology of tumor	Resection plan	Number of fibula osteotomies	Complication	Interincisal opening (mm)
1	46/ F	Osteosarcoma	C	4	No	45
2	44/ M	SCC	B	5	Dehiscence in donor area	42
3	52/ M	SCC	-	-	-	-
4	56/ M	SCC	B	-	No	48

SCC, squamous cell carcinoma.
Intraoperative and postoperative data were not available in the third patient because he did not undergo the operation after the planning.

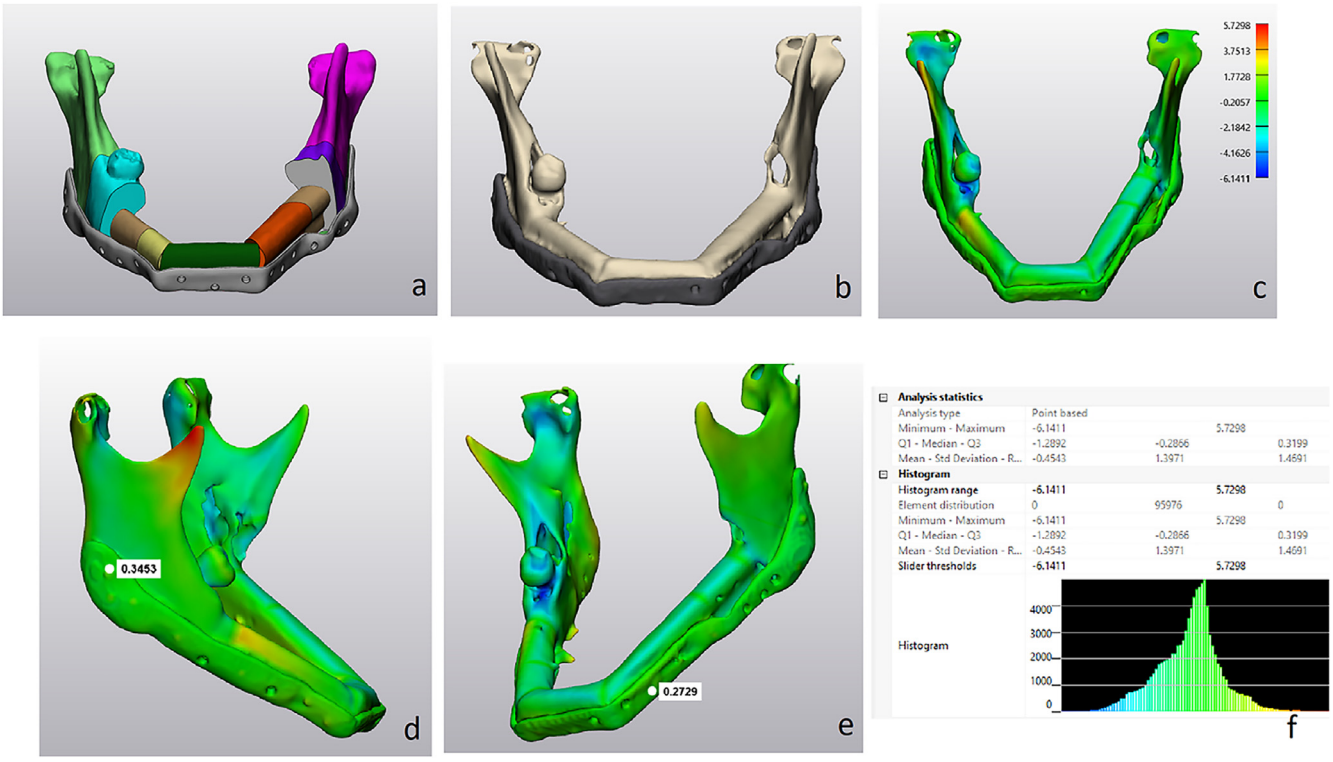

Fig. 6. A histogram analysis of the preoperative multisegment VSP and postoperative 3 months CT scan images: *a*- a preoperative design of the mandible reconstruction and implant through VSP; *b*- 3-dimensional model obtained from the conversion of the postoperative 3 months CT scan DICOM data; *c*- fusion analysis of *a* and *b* was performed; *d and e*- the differences between the same points of VSP and postoperative CT model were calculated in millimeters in three-dimensional coordinate system; *f*- a mean difference was – 0.45 mm, and standard deviation was found to be 1.39 mm (*VSP: virtual surgical planning; CT:computerized tomography; DICOM: digital imaging and communications in medicine*).

positive margins are confirmed. In the research about the surgical margins of mandibular osteosarcoma, it was reported that negative margins of peritumoral soft tissues are much more important than the bony margins in terms of obtaining local control and increasing overall survival [13]. Apart from its reconstructive success, multisegment resection planning enables the controlled resection of tumor with the distance of two centimeters in every step, and prevents uncontrolled mandibulectomy to obtain tumor- negative surgical margins.

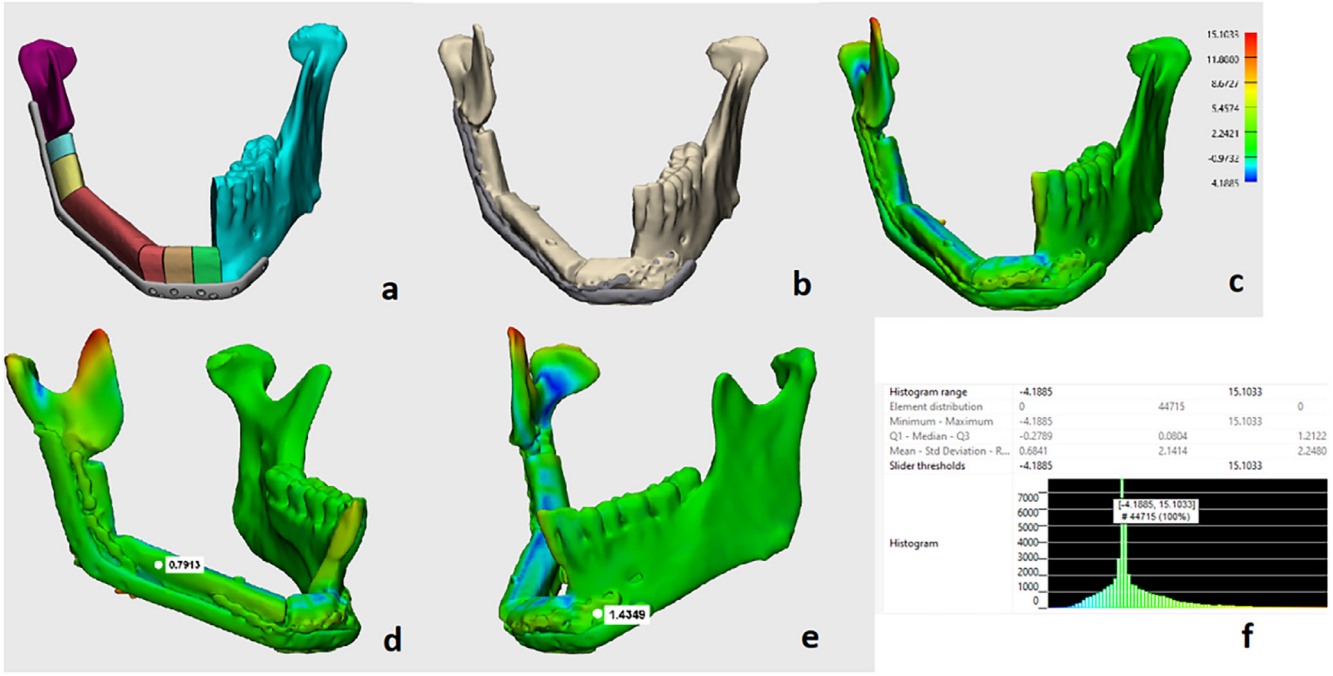

Fig. 7. A histogram analysis of the other patient. *a*- a preoperative design of the mandible reconstruction and implant through VSP; *b*- 3-dimensional model obtained from the conversion of the postoperative 3 months CT scan DICOM data; *c*- fusion analysis of *a* and *b* was performed; *d and e*- the differences between the same points of VSP and postoperative CT model were calculated in millimeters in three-dimensional coordinate system; *f*- a mean difference was – 0.68 mm, and standard deviation was found to be 2.14 mm (*VSP: virtual surgical planning; CT:computerized tomography; DICOM: digital imaging and communications in medicine*).

To obtain tumor-free margins the redundant resection can be avoided with this multisegment approach. The staged resection may decrease the morbidity of the patients in the healing period preventing the sacrifice of tumor-free teeth and bones. Although histopathological evaluation provides intraoperative feedback on bone marrow resection margin status and involvement of inferior alveolar nerve (IAN) it does not give information about the bone cortex. The specificity of IAN and bone marrow invasion is 100 % however sensitivity varies according to surgical and pathological methods. In their study, Bilodeau et al. specified the sensitivity as 50 %, whereas Oxford et al. reported that accuracy of intraoperative evaluation can be increased up to 89 % harvesting very thin bone segments [14,15]. Yet a negative frozen section of the IAN and bone marrow does not guarantee tumor-negative resection margins. In our study, inconsistency between the results of permanent specimen and intraoperative frozen section procedure was not encountered.

It has already been reported that VSP in mandible reconstruction has several advantages such as shortening of operation time, cost reduction, increase in reconstructive success, decrease in morbidities and length of hospitalization [16–18]. Additionally, in their comprehensive study in 2021, May et al. reported that complications such as malunion and nonunion were found significantly less in the patients who underwent the mandible reconstruction with VSP [19]. With the development in manufacturing industry production of patient- specific titanium implants took the virtual surgical planning a step further. In 2020, Lee et al. compared the outcomes of 126 patients who underwent the free fibula flap reconstruction with customized reconstruction plates [20]. According to their results, patient- specific plate was a significant independent predictor of a reduced number of overall complications and the length of hospital stay. Unlike the conventional VSP, the patient- specific implants manufactured in this study were designated to be compatible with the remaining mandibular segments and fibula flaps in each resection plan. Because the fibula segments are fixed to the implant on the surgical table, a three- dimensional guide is needed to obtain the accurate mandibular contour. In addition, to resemble the original mandibular contour with fibula segments only is prone to errors and up to the surgeon's experience; thus, implants were prepared to be in the same shape with the lower mandibular margin and provide continuity of the mandible. Hereby, the same contoured implant was able to be fixed to both mandibular and fibular segments easily regardless of resection plane.

The main limitation of multisegment virtual surgical planning is multiple fibula segments that should be considered while planning. It is known that free fibula flap has two sources of blood supply: endosteal and periosteal; and periosteal circulation pattern allows the fibula flap to be separated into multiple segments in several lengths up to 1 cm. [21] While planning in our study, care was taken not to reduce the length of fibula segments less than 1,5 cm. Moreover, a wide dissection area is required to place the patient- specific implant because it contains three resection plans and revealing most of the mandibular structures becomes inevitable even the resection plan A is applied. However, no viability problem in the mandible and fibula segments was encountered in the 3 months maxillofacial CT scans.

Multisegment virtual surgical planning including the multilevel resection and reconstruction can be successfully applied in the repair of mandibular defects due to several etiological factors, especially oncological conditions. This clinical trial was the preliminary study with a limited number of patients and future investigations are planned to compare the patients with multisegment VSP and conventional VSP with one resection level regarding to the requirement for exceeding of surgical margins and re-excision. Local tumor control is essential for preventing recurrence in the mandibular malignancies and long- term follow-ups are necessary to obtain clear data. A staged resection will prevent redundant removal of tumor- free mandible segments and teeth which can positively contribute to the morbidity of this population. Finally, multisegment VSP may be useful in the mandibular pathologies infeasible to detect the surgical margins preoperatively such as osteoradionecrosis etc., and situations in which unplanned resections are required to perform intraoperatively.

Ethical review committee statement

This study conformed to the Helsinki Declaration. We (all of the authors) confirm that we have read the Journal's position on issues involved in ethical publication and affirm that this report is consistent with those guidelines.

Ethical registration number

3/2022.K-80

Funding

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Ethical approval

Ethical approval was given to the study by ethical committee o Istinye University (ethical registration number: 3/2022.K-80).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Majid Ismayilzade: Writing – original draft, Resources, Formal analysis. **Kemalettin Yildiz:** Data curation, Writing – review & editing. **Halil Ibrahim Canter:** Conceptualization, Investigation, Project administration.

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All authors viewed and agreed to the submission.

Supplementary materials

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.jormas.2024.101859.

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