ORIGINAL ARTICLE

Development of a template tool for facilitating fibula osteotomy in reconstruction of mandibular defects by digital analysis of the human mandible

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Abstract

Objectives Mandibular reconstruction after segmental mandibulectomy can be challenging without virtual surgical planning and osteotomy guides. The purpose of this study was to analyze anatomic parameters to facilitate the evaluation of ideal fibula wedge osteotomies to reconstruct the neomandibula in a simple and cost-effective manner without the need for preoperative virtual planning.

Materials and methods Computed tomography scans were acquired from randomly selected patients, and all images were obtained from routine clinical diagnostics, e.g., tumor staging, or preoperatively before reconstruction. Data was used to calculate stereolithographic models of the mandible for length and angle measurements. Statistical analysis was performed ($p < 0.05$).

Results CT scans of 100 patients were analyzed: 39 were female and 61 were male patients, mean age was 59.08a. The mandibular arch angle proved to be constant with $241.07 \pm 2.39°$. The outside B-segment length was 80.05 ± 5.16 mm; the anterior S-segment length was 27.69 ± 3.16 mm. The angle of the mandibular arch showed differences in means ($p = 0.004$) between age groups, but effect was proved low. No relevant statistical significances were detected.

Conclusions The development of a mandible reconstruction template tool would benefit the majority of head and neck patients, which is due to a constant mandibular arch angle and symphysis segment length throughout the general patient population, allowing the mimicking of a harmonic mandibular arch with up to three fibula segments.

Clinical relevance The developed mandible reconstruction template tool can facilitate the fibula wedge osteotomies necessary for reconstruction of an ideal neomandibula providing a novel approach which is simple and cost-effective.

Keywords Mandible reconstruction · Head and neck anatomy · Reconstructive surgery · Digital morphology analysis · Fibula osteotomy · Microvascular fibula transplant

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Introduction

The bony reconstruction of the mandible by microvascular fibula free flaps after segmental mandibulectomy is an established standard procedure in reconstructive head and neck surgery. As first described in the maxillofacial region by Hidalgo et al. in 1989 [1], it was proved to be well suited for mandible reconstruction due to a long vascular pedicle, a wide vessel diameter, and the possibility to harvest a skin island and a muscle cuff. Further, a shortened operating time by a two-team approach for the vessel and transplant dissection is less physically demanding for the patient and the surgeon [2, 3]. Additionally, the fibula is the only bone transplant which allows reconstruction of the whole mandible with one single flap.

Nevertheless, surgeons are challenged by reconstructions of complex defects with one or more osteotomies in order to achieve a harmonic and functional neomandibular arch [4]. At the same time, the mandible plays an essential role for facial harmony, speech, mastication, and airway maintenance [5]. To address these vital roles of the mandible and to mimic it in the most accurate way possible, the exact adaption, segmentation, and forming of the fibula are essential. Therefore, the simulation of the mandibular contour correspondingly assumes the exact angles of the osteotomy and the bent plates. A feasible solution is seen in virtual surgical planning (VSP). VSP is increasingly applied for complex defect reconstructions, especially in two or more segmented mandible reconstruction cases to facilitate osteotomy and enhance accuracy. As a drawback, VSP is associated with higher financial costs and more intense preoperative planning. Furthermore, VSP has the drawback of a limited intraoperative flexibility. This could lead to have some safety risk, e.g., the resection margins are much larger than planned before and whole VSP therefore fails. In less complex reconstructive cases, the question remains if full-scale VSP with high additional preoperative effort and costs improves patient outcome. Efforts were made to address small defects by using stereolithographic (STL) models, silicon templates, and handmade cutting guides [6]. However, few tools to support osteotomy placement and segment design are available for microvascular fibular transplant reconstruction in head and neck surgery. During clinical routine, the experienced reconstructive surgeon is frequently confronted with more segmental bone defects, where full-scale VSP might be considered too laborious, but non-guided fibula reconstruction is challenging due to the correct osteotomy arches and the risk of impairing the pedicle and/or the skin perforators during transplant fitting and osteosynthesis. Consequently, the need for alternative methods without time-consuming preoperative planning and thus reduced financial overheads is evident. The aim of the study was the development of a surgical resection and reconstruction guide in order to facilitate fibula free flap reconstruction of the mandible. This consists of a template with an arbitrary symphysis segment and length-adjustable corpus segments. For the development and planning of the resection and reconstruction guide, detailed anatomic knowledge on the possible variations of angles and distances of the B- and S-segments of the human mandible was needed to cover the extensive variety of defect configurations. We therefore implemented a study on analyzing anatomic parameters of the human mandible with special focus on the variations in length of the B- and S-segments, as well as on the angles of the mandibular arch. Sufficient data on the anatomic values necessary for constructing an effective mandibular

reconstruction tool do not exist in the international literature. Hence, we evaluated existing CT scans for routine diagnostics of patients, generated corresponding digital 3D models, and performed exact measurements of clinically relevant values.

Materials and methods

Study design and data acquisition

To address the raised questions regarding the distribution of anatomic proportions of the human mandible for the development of a resection and reconstruction device for fibula free flaps, a retrospective cohort study was designed and implemented. The collection and analysis of the study's data was approved by the ethics committee of the Technische Universität München (registration number 459/18S). The research was conducted in accordance with the Declaration of Helsinki.

Study sample

The study included digital radiological data of high-resolution computed tomography (CT) scans from 100 randomly selected patients. All patients under the age of 16 years and with traumatic or pretreated mandibular defects as well as bony reconstructions were excluded. Patients with deformities of the mandibular, e.g., due to syndromic diseases or patients with dysgnathia were also excluded from the patient collective. The Digital Imaging and Communications in Medicine (DICOM) data was used for the calculation of 3D models for corresponding anatomic measurements. All patients eligible for the study were treated at the Department of Oral and Maxillofacial Surgery of the Klinikum rechts der Isar, Technische Universität München, and evaluated retrospectively. Radiological data of relevant cases was archived after treatment for further anatomic evaluation and digital 3D model preparation. CT scans were obtained as DICOM data files, and slice thickness had to be smaller than 1 mm for sufficient STL model resolution.

3D model preparation

The acquired DICOM data of relevant CT scans was matched with corresponding clinical patient data (e.g., age, sex, dental status), and measurement values were collected. DICOM data was imported into the Mimics software (Mimics Innovation Suite 19.0, Materialise, Leuven, Belgium). Radiological images were evaluated, and 3D models were calculated by using the software. Virtual tissue dissection was performed on the data set until only the bony mandible components remained.

Fig. 1 Illustration of the novel resection and cutting guide for mandibular reconstruction by free fibula flaps. The construction design of the two templates (above) and their clinical use (below)
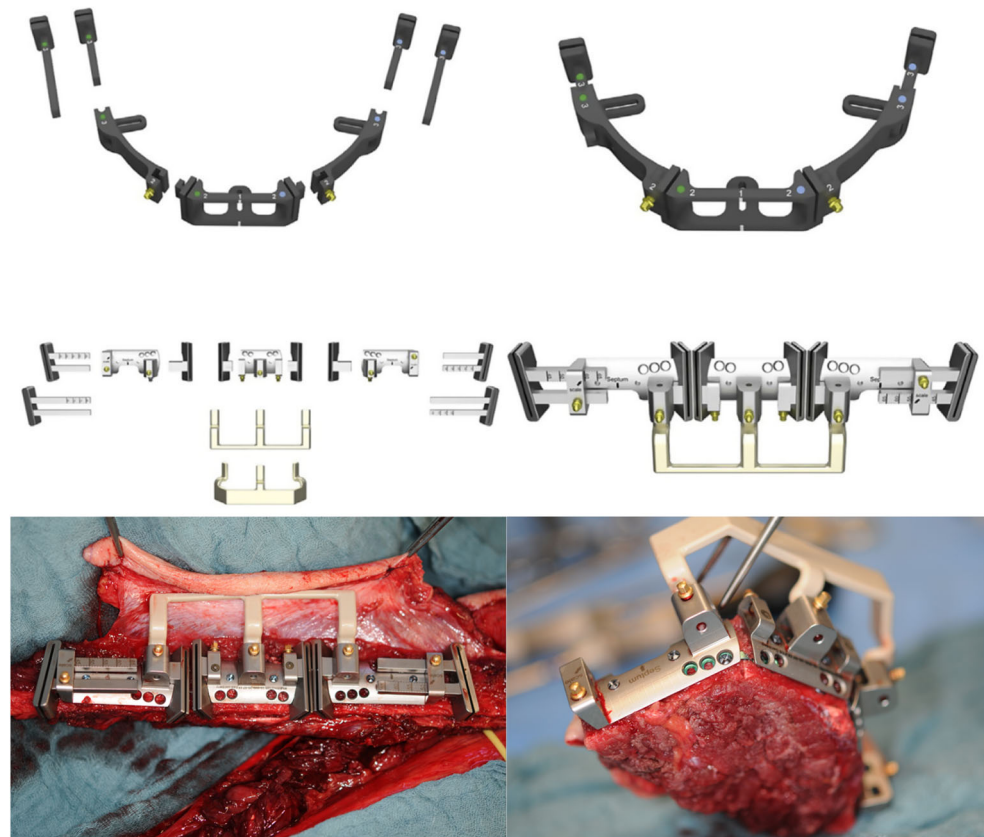
The model was then exported as an STL file for further processing and analysis (Fig. 1).

Anatomic measurement

The calculated STL files were imported into the netfabb software (netfabb Basic, version 5.2.1, Autodesk Inc., San Rafael, USA). The STL models were marked with defined points for distance and angle measurements. Resulting values were collected and used for further statistical analysis. The angle of the whole mandibular arch was measured on the caudal border of the mandible and consists of the left and right angles between the B- and S-segments (see Fig. 2). The length of the S- and B-segments on the lateral, medial, and caudal surface of the mandible were measured from the canine to the jaw angle in a parallel line to the base of the mandible (see Fig. 3). Condylar distances were measured between the mid- and most cranial surface point of the condyle (Co) on each side. Additionally, the distance from the condyle's surface to the gnathion (Gn), as the most caudal point of the mandible symphysis in the median-sagittal plane, was measured [7] (see Fig. 4).

Data analysis and statistical calculations

The obtained clinical patient data was correlated with measurement values from the 3D models. Statistical analysis on base data was performed for patient demographics and corresponding measurement value distribution. The SPSS 22.0.0 software (IBM SPSS, Inc., Chicago, IL, 2013) was used for statistical calculations. The Pearson correlations and t tests for independent samples were performed to evaluate associations between clinical variables (e.g., age, sex, dental status) and values of anatomic measurements. A p value < 0.05 was considered to be statistically significant.
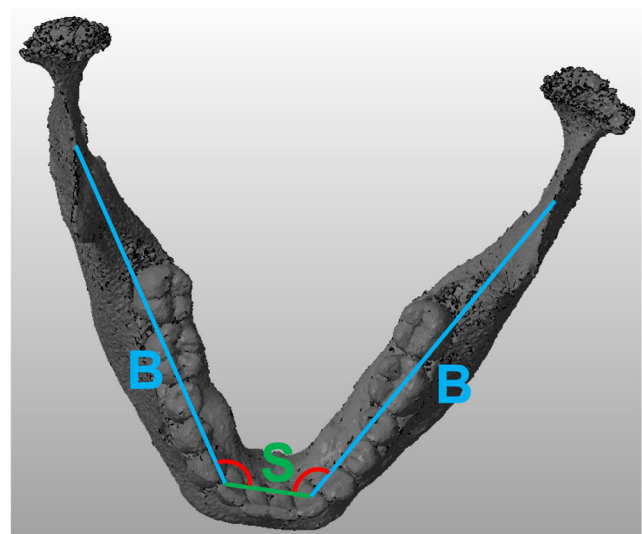

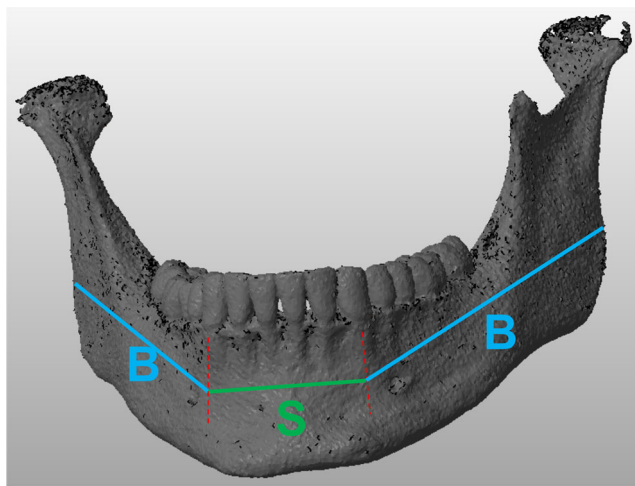**Fig. 2** The measurement of the mandibular arch angles

Fig. 3 The measurement of the B- and S-segments

Results

Altogether, the study reviewed and analyzed the radiological and clinical data of 100 patients with a normal state mandibula. All patients had recent CT scans, which were performed during routine diagnostics. DICOM data of relevant patients was acquired, and 3D models of the mandible were produced digitally. Out of the 100 included patients, 39 were female and 61 were male. The mean age of the patients was 59.08 years (median 60.5 years; SD 15.741; range 77 years; min–max 16–93 years). With regard to dental status, 20 patients (20%) were edentulous, 26 patients (26%) were partially edentulous (1–6 remaining teeth), and 54 patients (54%) were toothed (> 6 teeth) (see Table 1). The values of the various measurements of the mandible in detail are displayed in Table 2; the corresponding distances are illustrated in Fig. 4. The angle of the mandibular arch was proved highly constant in the measurement results. The overall value was 241.07° (SD ± 2.39°, range 16.68°, min 235.40°, max 252.08°); values
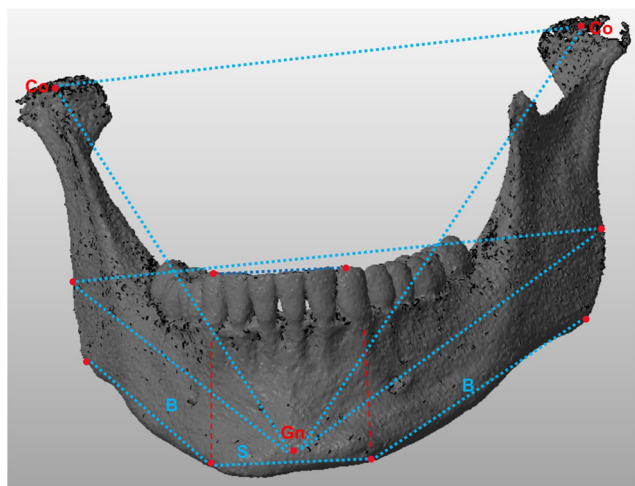

Fig. 4 Additional anatomic measurements

Table 1 Patient characteristics

		Overall ($n = 100$)
Age (years)	Mean (median)	59.08 (60.5)
	Range (min–max)	77 (16–93)
	SD	15.741
Sex (n (%))	Male	61 (61%)
	Female	39 (39%)
Dental status (n (%))	Edentulous	20 (20%)
	Partially edentulous	26 (26%)
	Toothed	54 (54%)

for the left side were 120.39° ± 1.68° and for the right side 120.68° ± 1.44°. The outside length of the B-segment was measured to be 80.05 mm (SD ± 5.16 mm, range 27.40 mm, min 68.81 mm, max 96.21 mm) and the length of the anterior S-segment was 27.69 mm (SD ± 3.16 mm, range 16.33 mm, min 20.62 mm, max 36.95 mm). The distance from the surface of the condyle (Co) to the anterior chin (Gn) was 124.83 mm (SD ± 6.84 mm, range 40.90 mm), between the two condyles (Co–Co) the length was 104.95 mm (SD ± 5.20 mm, range 30.21 mm), and between the two jaw angles the length was 98.89 mm (SD ± 7.20 mm, range 33.88 mm). The distance between the canine teeth could be measured in 75 patients and was 26.21 mm (SD ± 2.07 mm, range 11.76).

The mandibular arch angle showed a positive correlation with age ($p = 0.002$) and a negative correlation with the parameters depicting the sagittal mandibular length, e.g., lateral B-segment ($p = 0.009$), caudal B-segment ($p = 0.012$), medial B-segment ($p = 0.009$), caudal S-segment ($p = 0.003$), jaw angle–Gn ($p = 0.002$), and Co–Gn ($p = 0.008$).

The angle of the mandibular arch showed differences in means ($p = .004$) between age groups (threshold 50 years), but the effect was proved low (Cohen $r = .12$). Other relevant statistical significances could not be detected. Referring to this data, we started the development of a surgical resection and reconstruction guide which consists of a template with an arbitrary symphysis segment and length-adjustable corpus segments.

The construction plan contained a cutting guide for the mandible as well as the fibula, both having a sliding bar for individual adjustment of the segment length for the corpus. Resection was performed after placement of the resection template on the lower jaw for one, two, or three segments, e.g., B, SB, or BSB, according to the classification by Urken [8]. The extension of the B-segments could be measured, and the adjusted length was transferred to the fibula template, where concordant osteotomies were performed. Afterward, the exact positioning of the segments and corresponding osteosynthesis was supported by the template (Fig. 1). The development was performed in collaboration with an industrial partner (KLS Martin, Tuttlingen, Germany).

Table 2 Measurement results

	Left	Right	overall ($n = 100$)
SB angle (° ± SD)	120.39 ± 1.68	120.68 ± 1.44	241.07 ± 2.39 (range 16.68)
S anterior (mm ± SD)			27.69 ± 3.16 (range 16.33)
B outside (mm ± SD)	80.30 ± 5.06	79.79 ± 5.33	80.05 ± 5.16 (range 27.40)
B inside (mm ± SD)	76.52 ± 4.86	76.68 ± 4.88	76.60 ± 4.84 (range 25.66)
S basal (mm ± SD)			26.47 ± 3.19 (range 15.72)
B basal (mm ± SD)	69.36 ± 4.91	69.26 ± 5.10	69.31 ± 4.97 (range 28.37)
Co–Gn (mm ± SD)	124.27 ± 6.32	125.39 ± 8.62	124.83 ± 6.84 (range 40.90)
Co–Co (mm ± SD)			104.95 ± 5.20 (range 30.21)
Jaw angle–jaw angle (mm ± SD)			98.89 ± 7.20 (range 33.88)
Jaw angle–Gn (mm ± SD)	95.38 ± 5.96	95.20 ± 6.33	95.29 ± 6.06 (range 33.07)
			($n = 75$)
Canine–canine (mm ± SD)			26.21 ± 2.07 (range 11.76)

Condylus (Co): mid- and most cranial surface point of the mandibular condyle

Gnathion (Gn): most caudal point of the mandible symphysis in the median-sagittal plane

Discussion

Microvascular fibula free flap is regarded as standard treatment for reconstruction of the mandible. The key to mimicking the human jaw in the most natural way possible is to perform the ideal fibula osteotomies and follow osteosynthesis of the segments in order to achieve a harmonic mandibular arch. VSP is increasingly applied especially in two or more segmented mandible reconstruction cases to facilitate osteotomies and thus enhance accuracy. Several authors describe advantages of this method regarding reduced operating time and increased precision of reconstruction with comparable complication rates [2, 4, 9–17]. Critical points are the additional costs and time for preoperative planning and that the strategy is superfluous in the case of positive margins or other reasons for intraoperative treatment concept modification [18–20]. While changing, the surgical strategy is getting easier with increasing experience in this technique; costs are a serious matter against the background of cost-effectiveness as well as clinical outcomes as a benchmark for hospitals and insurance carriers [21]. As an alternative to VSP-planned cutting guides, Pirgousis et al. reported the ideal fibula wedge osteotomy to recreate the mandibular angle by using an autoclavable metal wedge of about 56° [5]. Their team measured the angle of the mandibular angle in 60 patients and produced a wedge respecting the average angle of all measured patients. This simple but well-designed technique is very well suited for reconstructions of defects of the body and ascending ramus, e.g., BR according to the classification of Urken [8]. However, many mandible reconstructions, especially after tumor ablation due to oral squamous cell carcinoma infiltration in the anterior part of the mandible, require reconstruction of the body and symphysis region (BS or BSB). As no technique to facilitate the reconstruction of this angle has been described at present, the aim of this study was to analyze the angle of different patients to find a standard angle for the symphysis body region.

We therefore implemented a study based on radiological data from high-resolution CT scans, which were performed on patients during routine oral and maxillofacial diagnostics. DICOM data from the scans were then used for digital 3D-model generation, and anatomic measurements were performed. These examinations revealed harmonic statistic results (see Table 2). The angle of the mandibular arch is highly constant with $241.07° \pm 2.39°$ and not mainly influenced by age and sex. Therefore, it is possible to achieve a harmonic and natural neomandibular arch with a three-segmented fibula and fixation angles between the two BS segments of 120° on each side. Furthermore, the S-segment also proved to be relatively constant and independent from other parameters with 27.69 mm ± 3.16 mm. The B-segment was however the parameter with more distributed values of 80.05 mm ± 5.16 mm (range 27.40 mm). Hence, it was possible to construct a single template device for all patients independent of gender or age. The length of the symphysis (S-segment) and the angles between corpus and symphysis (BS angle) could be standardized, due to their constant length. The length of the corpus (B-segment) however has to allow an individually adjustable length. With the length of the symphysis segment being fixed to about 27 mm and not designed to be adjustable, it was important that this length does not lead to malperfusion. The selected length for the anterior segment was estimated to be a safe segment length with regard to bone perfusion, as similar values have been used by the authors previously and throughout the literature without leading to complications [22–24]. Based on this data, the planned fibula free flap reconstruction templates could now be designed and constructed [25].

The developed fibula reconstruction tool can be both used on the patients' left and right fibulas without difference. It is designed for the standard case of harvesting the right fibula with anastomosis on the left neck side and intraoral skin paddle position or harvesting the left fibula with anastomosis on the right neck side and intraoral skin paddle position. The template tool can also be used in non-standard cases. For these situations, the outer osteotomy guides have to be exchanged with each other. This adaption is used for harvesting the right fibula with anastomosis on the right neck side and extraoral/small skin paddle or harvesting the left fibula with anastomosis on the left neck side with extraoral/small skin paddle. The anatomic data generated in this study with special focus on the relevance for head and neck reconstructive surgery is unique in the international literature. Several studies have been published on the subject of anatomic mandible data, but most of these are unsuitable for questions on bony reconstruction. Watanabe et al., for example, measured height and width of human mandibles and the path of the canal of the inferior alveolar nerve with respect to implantological questions, without referring to mandibular angles and segment length [26]. Miller et al. also analyzed the mandible with regard to implantological issues, especially focusing on the symphysis region [27]. Deguchi et al. analyzed the volumes of the maxilla and the mandible as well as their respective ratio with regard to dysgnathia patients [28]. However, the study did not provide values useful for the development of a fibula reconstruction template tool. A study performed by Kano et al. on postmortem CT scans of Japanese subjects with the aim of facilitating gender determination by analyzing anatomic angles and landmarks of the mandible featured some of the values also represented in our data [29]. In this study, special focus was given to the mental region, as chin differences between genders are most distinct. Due to the different placement of the measurement points, a general comparison to our data evaluation is not possible even though some of the measured values are overlapping. At least for the distance between the jaw angles, the selected points of measurement are comparably equal and the related values are very similar (e.g., means in length from Kano et al. are 102.9 mm for male/95.8 mm for female patients, compared with 101.8 mm for male/94.4 mm for female subjects in this study). However, this data does not provide the relevant information to reconstruct a standardized neomandible. Consequently, to this day, there is no anatomic data published in the international literature displaying the necessary values for the development of a template tool for mandible reconstruction with fibula free flap, thus highlighting the importance of this study.

Conclusion

It can be concluded that the development of a standardized template tool for mandible reconstruction with fibula free flap is possible, due to a constant mandibular arch angle of about

240° and a symphysis segment length of 27.69 mm throughout the general patient population. The corpus length, by contrast, is the only part which needs to be adaptable to different mandibular extensions. The design and development of a standardized reconstruction device have already started, and the clinical testing and implementation process are ongoing. The expected release and thus common availability of the template system is scheduled for the second half of 2019.

Compliance with ethical standards

Conflict of interest The fibula reconstruction templates were jointly developed with Gebrüder Martin GmbH & Co. KG, KLS Martin Group, Tuttlingen, Germany. The Department of Oral and Maxillofacial Surgery, Klinikum Rechts der Isar, Technische Universität München received financial funding for the development. The authors declare to have no further conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee (Technische Universität München, registration number 459/18S) and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. This article does not contain studies with animals performed by any of the authors.

Informed consent Informed consent was obtained from all individual participants included in the study.

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