A NOVEL DIGITAL METHOD FOR EVALUATION OF MUCOSA THICKNESS CHANGES IN TIME: CHANGES ASSOCIATED WITH A REMOVABLE PARTIAL DENTURE

MARKO KURALT[1,2], MANUSHAQE SELMANI BUKLETA[2,3], MILAN KUHAR[4,5], AND ALEŠ FIDLER[✉,1,6]

[1]Department of Restorative Dentistry and Endodontics, University Medical Centre Ljubljana, Slovenia; [2]Faculty of Medicine, University of Ljubljana, Slovenia; [3]School of Dentistry, Faculty of Medicine, University of Prishtina, Kosovo; [4]Department of Prosthetic Dentistry, Faculty of Medicine, University of Ljubljana, Slovenia; [5]Department of Prosthodontics, University Medical Centre Ljubljana, Slovenia; [6]Department of Endodontics and Operative Dentistry, Faculty of Medicine, University of Ljubljana, Slovenia
e-mail: marko@kuralt.si; manushaqeart@gmail.com; milan.kuhar@mf.uni-lj.si; ales.fidler@mf.uni-lj.si
(Received July 16, 2022; revised October 4, 2022; accepted October 10, 2022)

ABSTRACT

The aim of the study was to propose a method for three-dimensional evaluation and visualisation of mucosa thickness and mucosa thickness changes and to validate it in four different software implementations. Cone-beam computed tomography (CBCT) and digitised mandibular impression, i.e., optical scan, of five patients treated with a mandibular distal extension removable partial denture were acquired at baseline (T0) and 1-year follow-up (T1). CBCT images were automatically segmented and then superimposed with a corresponding optical scan and within a patient. To obtain mucosa thickness changes in the T0-T1 interval, firstly, the distances between T0 and T1 models were computed for mucosa surface, representing surface changes (dSurface) and bone surface, representing bone changes (dBone). The distances were saved as scalar field values in the mesh model. Finally, the mucosa thickness changes (dMucosa) were calculated by subtracting the corresponding dBone from dSurface values. Distance computation algorithms in four different software were tested and compared. No differences were found between all four tested software (p<0.001). Mean (and standard deviation) of median dSurface, dBone, and dMucosa of right and left residual ridge (n=10) was -0.47mm (0.43), -0.44mm (0.62), and 0.00mm (0.35), respectively. High local variability of dBone and dMucosa was found on the colour-coded maps. A novel method facilitates precise three-dimensional evaluation and visualisation of mucosa thickness and thickness changes, regardless of the software used.

Keywords: cone beam computed tomography; image analysis; optical scanning: oral mucosa; removable partial denture.

INTRODUCTION

Developments in the imaging technologies in dentistry, such as cone-beam computed tomography (CBCT) and optical scanning, revolutionised the field in research and clinical setting (Gaêta-Araujo *et al.*, 2020; Shujaat *et al.*, 2021). CBCT enables the evaluation and visualisation of mineralised structures such as bones and teeth that are not visible at clinical examination. It presents a smaller radiation dose and higher spatial resolution than medical computed tomography (Jacobs *et al.*, 2018). While optical scanning, especially recently introduced intraoral scanning, is an entirely non-invasive method used to capture the surface of intraoral structures, such as teeth and soft tissues (Mangano *et al.*, 2017). Digital models obtained with the modalities mentioned above are represented as polygonal surface meshes. Optical scanning requires no additional processes, as surface meshes are generated during the acquisition process, while the CBCT images require prior segmentation of anatomical structures of interest (Verhelst *et al.*, 2021). In the past, segmentation of CBCT images often presented a challenge mainly due to unstandardized grey voxel values and artefacts (Friedli *et al.*, 2020; Hassan *et al.*, 2010; Pauwels *et al.*, 2015; Schulze *et al.*, 2011). However, the recent introduction of deep learning and artificial intelligence (AI) for the segmentation of CBCT images made the process time-efficient and more reproducible (Shaheen *et al.*, 2021; Verhelst *et al.*, 2021).

Removable partial dentures (RPDs) are still widely used in clinical practices to treat partial edentulism, despite other predominant treatment options, including fixed partial dentures and implants (Douglass &

Watson, 2002; Ramsay *et al.*, 2015). A recent review on RPDs (Campbell *et al.*, 2017) emphasised the need for innovation regarding novel materials (Najeeb *et al.*, 2016; Srinivasan, Kalberer, Kamnoedboon, *et al.*, 2021) and fabrication technologies (Alammar *et al.*, 2022; Piedra-Cascón *et al.*, 2021; Revilla-León *et al.*, 2020; Srinivasan, Kalberer, Fankhauser, *et al.*, 2021) due to the limitations associated with existing RPDs (Benso *et al.*, 2013; Preshaw *et al.*, 2011; Saito *et al.*, 2002). During mastication, the mucosa plays a critical role in distributing and withstanding occlusal forces transferred through the denture to the underlying bone (Kumar, 2014; Żmudzki *et al.*, 2015). In the past, evaluation of bone changes of the residual ridge was the main emphasis in the evaluation of denture-supporting tissue changes (Ahmad *et al.*, 2013; Blum & Fraser McCord, 2004; Ozan *et al.*, 2013; Tallgren, 2003). Occlusal forces exerted on the denture supporting bone can significantly increase resorption of the residual ridge; otherwise, an irreversible physiological process and consequently leads to poor denture fit (Saito *et al.*, 2002). Recently, significant interest has arisen in evaluating mucosa (Chen *et al.*, 2015; Dong *et al.*, 2015). The mucosal response to dentures has exhibited complex nonlinear and time-dependent behaviours (Cook, 1991; Khamis Abdel Razek & Shaaban, 1978). Furthermore, mucosa thickness has been established as one of the main factors affecting biomechanical response. However, there seems to be a lack of clinical studies quantifying and describing mucosal changes associated with denture wearing. Superimposed segmented CBCT images and optical scans were recently utilised in a study evaluating bone and mucosal surface changes associated with wearing RPDs (Kuralt *et al.*, 2019). The study's main limitation was the lack of mucosal thickness changes. From an anatomical point of view, the mucosa is a flat structure covering the underlying bone. Changing its thickness might compensate for changes in the underlying bone, thus retaining the same surface morphology. The bone and mucosa surface changes can be simply calculated by measuring the difference between two models, i.e. bone or surface. In contrast, the mucosa thickness change results from changes of four models, i.e. two bone and two surface models, obtained at two-time points and is much more complicated for evaluation.

Thus, the present study aimed to propose a novel method for three-dimensional evaluation and visualisation of mucosa thickness changes, using CBCT and optical scanning, and to validate it in four different software implementations.

MATERIALS AND METHODS

PATIENTS AND IMAGE DATA ACQUISITION

This methodological study is a part of a research project evaluating the effect of prosthodontic treatment of partially edentulous patients on oral health. Ethical approval was obtained from the Ethics Committee of Hospital and University Clinical Service of Kosovo and University Clinical Centre of Kosovo (555/18.05.2017). In addition, all patients were informed of the study protocol and gave their written consent to participate. Patients of both genders between 45 and 65 years old with a bilateral edentulous area distal to the remaining natural teeth (Kennedy class I status of partial edentulism) were included in the project. The patients had no previous prosthodontic treatment and were without active caries lesions and periodontal disease.

All patients were treated with a mandibular distal extension RPD and underwent clinical and radiographical examination at baseline (T0), including a CBCT and a mandibular impression. After one year (T1), a clinical and radiographical examination was repeated, including a CBCT scan and an impression. For a more detailed description of the data acquisition, readers are referred to the study of Kuralt *et al.* (Kuralt *et al.*, 2019). In brief, all CBCT scans were taken with an ORTHOPHOS XG 3D device (Dentsply Sirona) with the following scanning parameters: field of view (FOV) 8×8 cm, voxel size 0.16 mm^3, 85 kV and 7 mA and 10 mA for female and male patients, respectively. Scans were exported in DICOM format. At the same time, mandibular impressions were taken with an irreversible hydrocolloid impression material (XantALGIN Select Fast Set; Heraeus Kulzer GmbH) and poured with gypsum immediately after making. Casts were digitised with a laboratory optical scanner (Ceramill Map 400; Amann Girrbach AG) and exported in Standard Tessellation Language (STL) file format. The first five patients' image data were used for this methodological study.

IMAGE SEGMENTATION AND SUPERIMPOSITION

A CBCT and optical scans for each patient and time-point were uploaded to the cloud-based platform "Virtual Patient Creator" (https://creator.relu.eu, Relu BV), offering AI-assisted segmentation and superimposition of dental and maxillofacial images. Mandible and teeth were automatically segmented on CBCT image and superimposed with an optical scan of mandibular cast model using teeth. Furthermore, CBCT

images with corresponding optical scans from both time points were superimposed manually using GOM Inspect (version 2018, GOM GmbH) with a selection of stable regions on the body of the mandible (Fig. 1).

Finally, all four superimposed surface meshes per patient were exported in STL file format for further analysis.
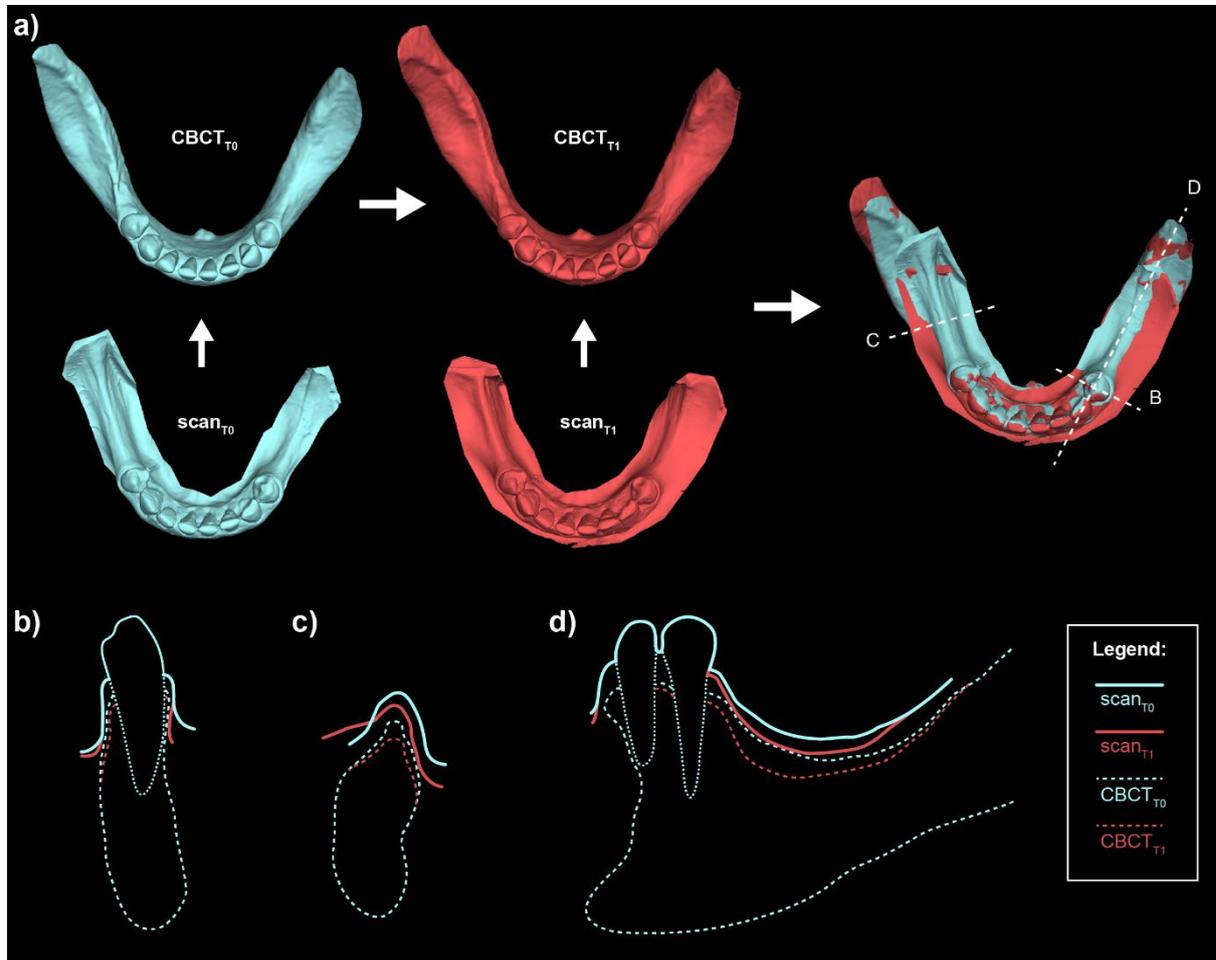

Fig. 1: *Superimposition of cone-beam computed tomography (CBCT) and optical scans, i.e., digitised impressions, per patient from baseline (T0) and follow-up (T1) (a). Teeth surfaces were used to superimpose multi-modal images, i.e., CBCT and optical scan. In contrast, for multi-temporal data, i.e., CBCT scans from T0 and T1 with corresponding already superimposed optical scans, stable anatomical regions on the mandibles body were used, i.e., left and right mental foramina and mental spine. In addition, two buccal-oral cross-sections were made (B and C), indicating regions without (b) and with changes (c) and one mesio-distal cross-section (D), combining both regions (d).*

EVALUATION AND VISUALISATION OF DENTURE SUPPORTING TISSUES

Distances were computed between superimposed meshes, i.e., $CBCT_{T0}$, $CBCT_{T1}$, $scan_{T0}$, and $scan_{T1}$, obtaining surface change (dSurface) and bone thickness change (dBone), and mucosa thickness ($mucosa_{T0}$ and $mucosa_{T1}$) (Fig. 2). A "cloud to mesh" algorithm, i.e., an algorithm that finds the minimum Euclidean distance from each vertex or point of a mesh (reference mesh) to the closest triangle on a different mesh

(compared mesh), was used in CloudCompare (version 2.12 alpha).

dSurface and dBone were obtained by computing distances between the meshes acquired with the same modality at T0 and T1, i.e., $scan_{T0} - scan_{T1}$ and $CBCT_{T0} - CBCT_{T1}$, respectively. While mucosa thickness was obtained by computing distances between the meshes acquired with different modalities, i.e., scan – CBCT, either at T0 or T1, representing baseline and follow-up thickness. Computed distances

were saved as vertex attributes, i.e., a scalar field value assigned to each vertex or point on the reference mesh.

To obtain mucosa thickness changes (dMucosa), obtained scalar field values were further calculated using the "Arithmetic" algorithm in CloudComapare (Fig. 2). First, dBone was computed on a $scan_{T0}$ as a reference mesh by subtracting $scan_{T0} - CBCT_{T0}$ and $scan_{T0} - CBCT_{T1}$ scalar fields. Second, dBone was subtracted from dSurface to obtain dMucosa displayed on $scan_{T0}$ mesh.

For further evaluation, a region of interest (ROI) was defined on a central residual ridge area, limited to a firmly attached masticatory mucosa with a width of four millimetres. Such ROI was defined due to the mobility of loosely attached alveolar lining mucosa in the denture foundation area, as previously reported by Kuralt *et al.* (Kuralt *et al.*, 2019) (Fig. 2a). ROI was defined with surface curves in GOM Inspect. First, surface curve was created from mesial to distal edge on the top of the residual ridge. Then, an offset of two millimetres was used to create surface curves on each side of the residual ridge resulting in a four millimetres wide surface area. Edge surface curves were exported to CloudCompare, where the "Segment tool" was used for the actual ROI selection.

Scalar field values were visualised with mapping values to colour using the transfer function. Two different colour maps were selected, i.e., linear Viridis to display mucosa thickness (Kuralt *et al.*, 2020) and diverging rainbow to display tissue thickness changes (Kuralt *et al.*, 2019).
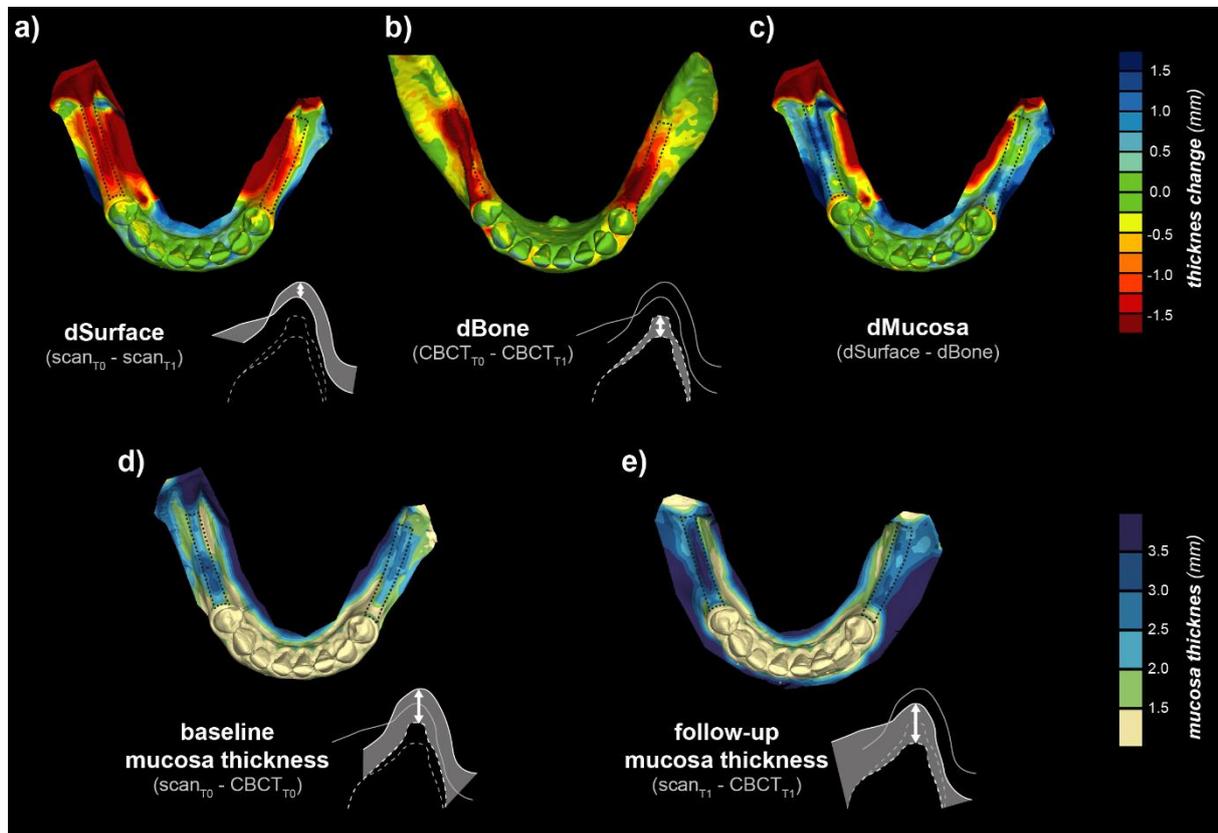

Fig. 2: *A geometric approach with distance computation between superimposed multi-modal and temporal meshes, i.e., cone-beam computed tomography (CBCT) and optical scans (scan) from baseline (T0) and follow-up (T1). Distances represent either surface thickness changes (dSurface) (a), bone thickness changes (dBone) (b), and baseline or follow-up mucosa thickness (d and e) displayed with colour mapping, i.e., a transfer function assigning a colour for each distance value. For example, to obtain mucosa thickness changes (dMucosa) dBone is subtracted from dSurface for each point of the polygonal surface mesh (c).*

VALIDATION OF THE PROPOSED EVALUATION METHOD

Four different analysis software and their implementation of the "cloud to mesh" distance computing algorithm were compared regarding mucosa thickness (n=20), dSurface (n=10), and dBone (n=10) on the defined ROI. Besides CloudCompare, GOM Inspect, MeshLab (version 2021.10), and 3D Slicer (version 4.11.20210226) were used. The comparison was performed in CloudCompare by subtracting the scalar fields enabling point-to-point comparison. Additionally, a comparison of dBone computed on $CBCT_{T0}$ and $scan_{T0}$ reference mesh was made, representing a methodological error in dMucosa calculations.

STATISTICAL ANALYSIS

Statistical analysis was carried out using GraphPad Prism 9 (version 9.3.0, GraphPad Software). Descriptive statistics were obtained, including mean, standard deviations, median, minimum, and maximum values. In addition, the mean absolute differences between tested distance computation algorithms were assessed using the one-sample t-test to determine if mean differences were statistically different from zero.

RESULTS

DENTURE SUPPORTING TISSUES THICKNESS CHANGES

The mean (and standard deviation) of minimum, median, and maximum dSurface per study sample of five mandibles with right and left residual ridge (n=10) was -1.29 mm (0.58), -0.47 mm (0.43), and 0.29 mm (0.48), respectively. For dBone, the results were -1.15 mm (0.84), -0.44 mm (0.62), and 0.29 mm (0.49), respectively. And for dMucosa, the results were -1.32 mm (0.60), 0.00 mm (0.35), and 0.88 mm (0.42). Distribution for each parameter and ROI per patient is displayed with colour-coded maps (Fig. 3) and boxplots (Fig. 4)

MUCOSA THICKNESS

The mean (and standard deviation) of minimum, median, and maximum baseline mucosa thickness per study sample was 1.26 mm (0.41), 2.41 mm (0.45), and 3.50 mm (0.54), respectively. While, for follow-up mucosa thickness, the results were 1.10 mm (0.50), 2.42 mm (0.51), and 3.42 mm (0.62), respectively. Distribution for each parameter and ROI per patient is displayed with colour-coded maps (Fig. 5) and boxplots (Fig. 6).

VALIDATION OF THE PROPOSED METHOD

The mean of the absolute difference between all tested distance computation algorithms for dSurface, dBone, and mucosa thickness was less than 0.0001 mm (p<0.001). The mean (and standard deviation) of absolute differences between dBone computed on $CBCT_{T0}$ and $scan_{T0}$ reference mesh was 0.06 mm (0.05).

DISCUSSION

The present study proposed a novel method for precise evaluation and visualisation of soft tissue thickness changes resulting from the acquisition of underlying bone changes and mucosa surface changes. Using CBCT and optical scanning, an innovative geometric approach is based on distance computation between surface meshes and scalar fields to enable three-dimensional evaluation. Four different software implementations of distance computation algorithms did not show any differences, thus validating their use. Furthermore, in a study sample, high local variability of mucosa changes associated with wearing a denture was found with a novel method, emphasising the importance of a novel method to understand better the dynamics of the denture supporting tissues.

A novel geometric approach facilitated a comprehensive three-dimensional evaluation of mucosal changes. The geometric approach relies on distance computation between meshes and assigning distance values for each point of the reference mesh creating a scalar field. Scalar field values are utilised for further analysis, such as descriptive statistics of an ROI or visualisation using colour mapping. Colour mapping is an efficient way to display differences between the two surfaces. The novelty of the presented method was the calculation between multiple scalar fields assigned to one surface mesh. In such a way, dMucosa was obtained for each mesh point by subtracting dBone from dSurface scalar field. In contrast to the volumetric approach (Kuralt *et al.*, 2019), the geometric approach can depict the spatial distribution or local variability of the scalar values of interest (Thiery *et al.*, 2017). Colour scale selection and threshold definition are essential for detecting relevant variability (Crameri *et al.*, 2020; Kuralt *et al.*, 2020). The high variability of dMucosa observed on an individual level further emphasised the importance of the novel method.

Additionally, the novelty of the presented method, i.e., scalar fields calculation, was also used to compare different software, revealing negligible differences between the software and confirming the method's robustness.

Accurate superimposition of multi-modal and temporal images represents the first step toward three-dimensional evaluation of tissue dynamics. The concept of virtual patient, i.e., combining multimodal images such as intraoral scanning, face scanning, and CBCT (Mangano *et al.*, 2018; Shujaat *et al.*, 2021; Unkovskiy *et al.*, 2021), is a recent well-accepted clinical approach to treatment planning in dentistry. The concept was enhanced for research purposes in the present study, adding the fourth dimension, i.e., time.
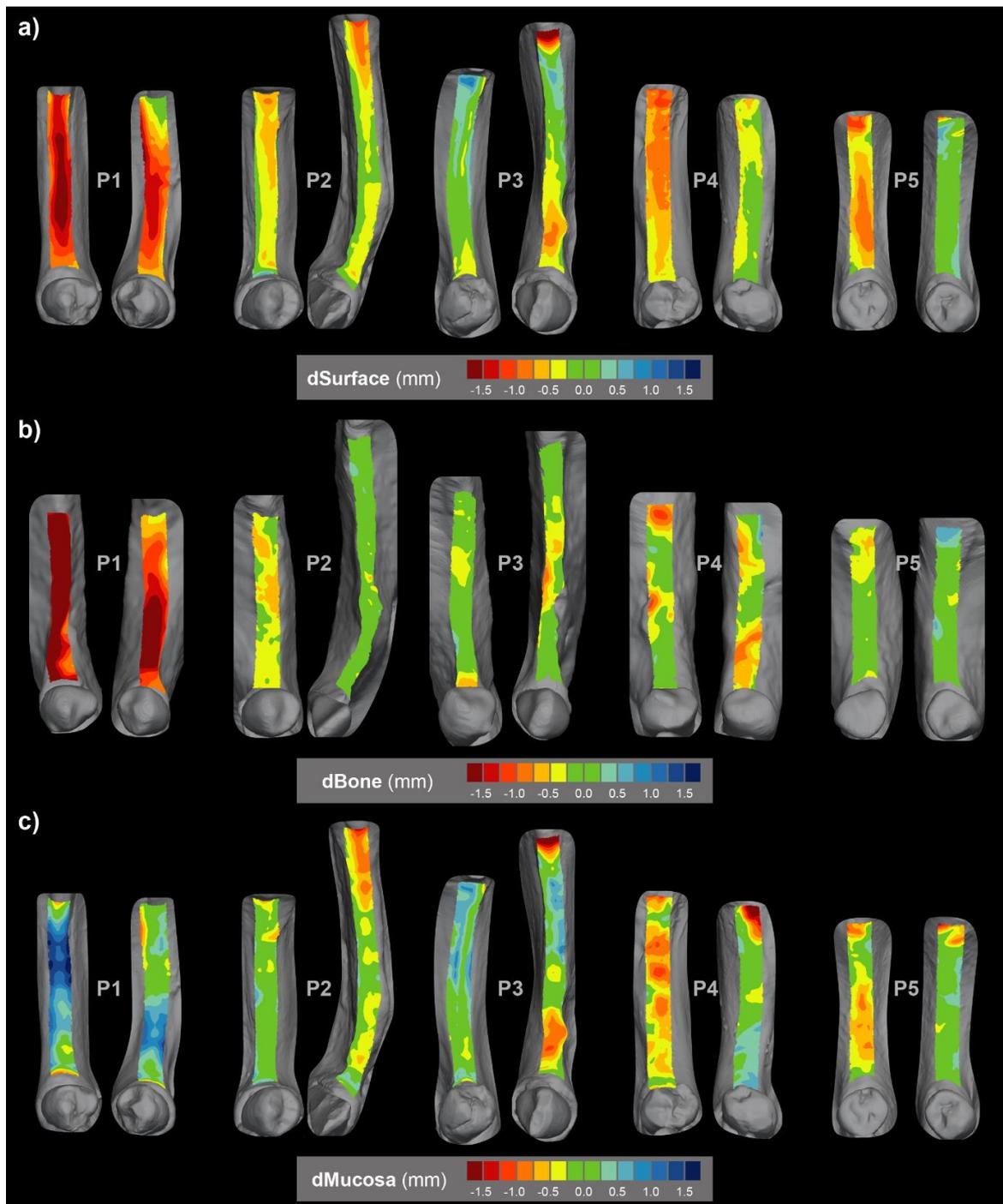

Fig. 3. *Surface (dSurface) (a), bone (dBone) (b), and mucosa thickness changes (dMucosa) (c) were visualised on the right and left residual ridges for all patients included in the present study.*
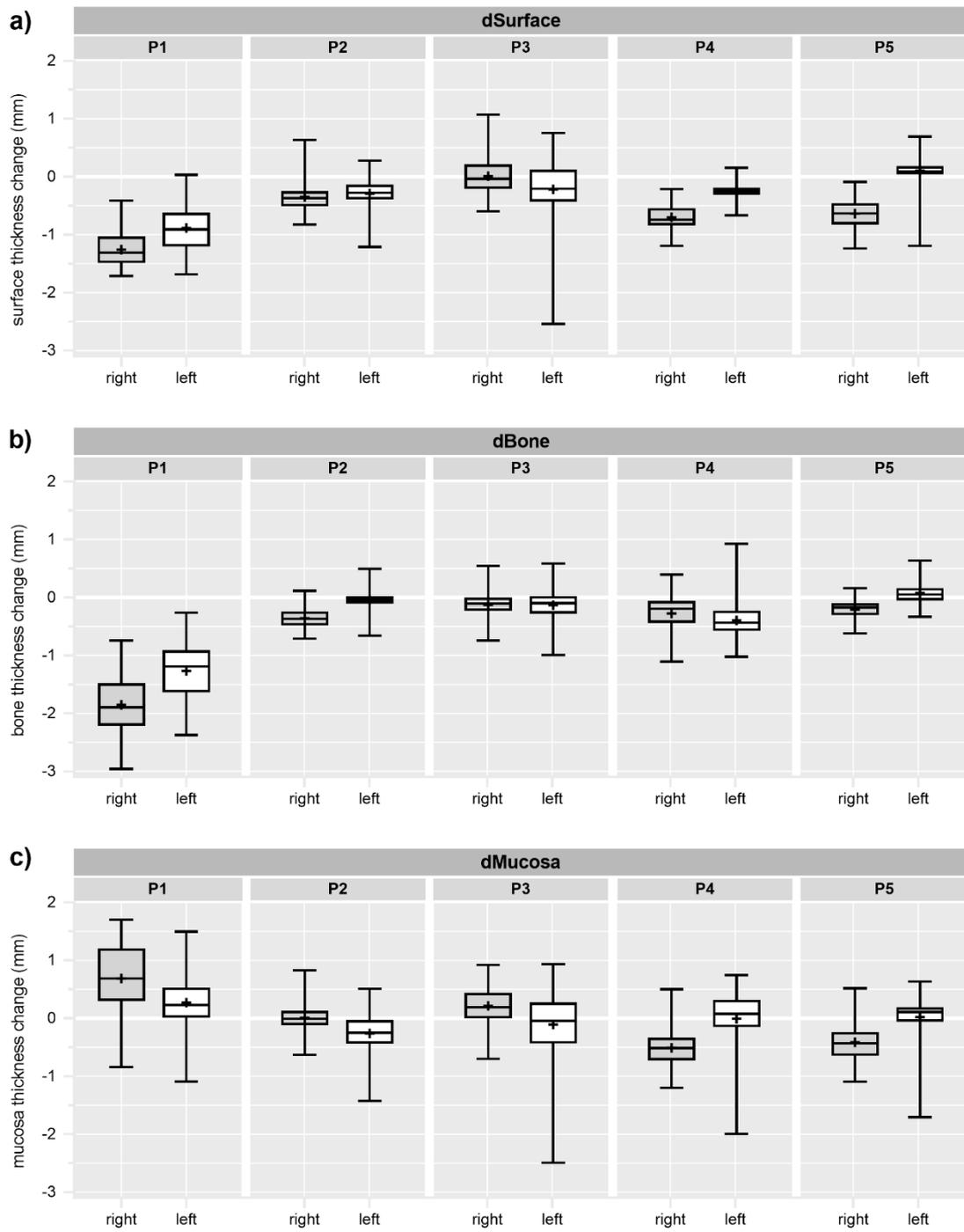
Fig. 4. *Distribution of surface (dSurface) (a), bone (dBone) (b), and mucosa thickness changes (dMucosa) (c) of the right and left residual ridges for all patients (P) included in the present study were displayed with boxplots.*
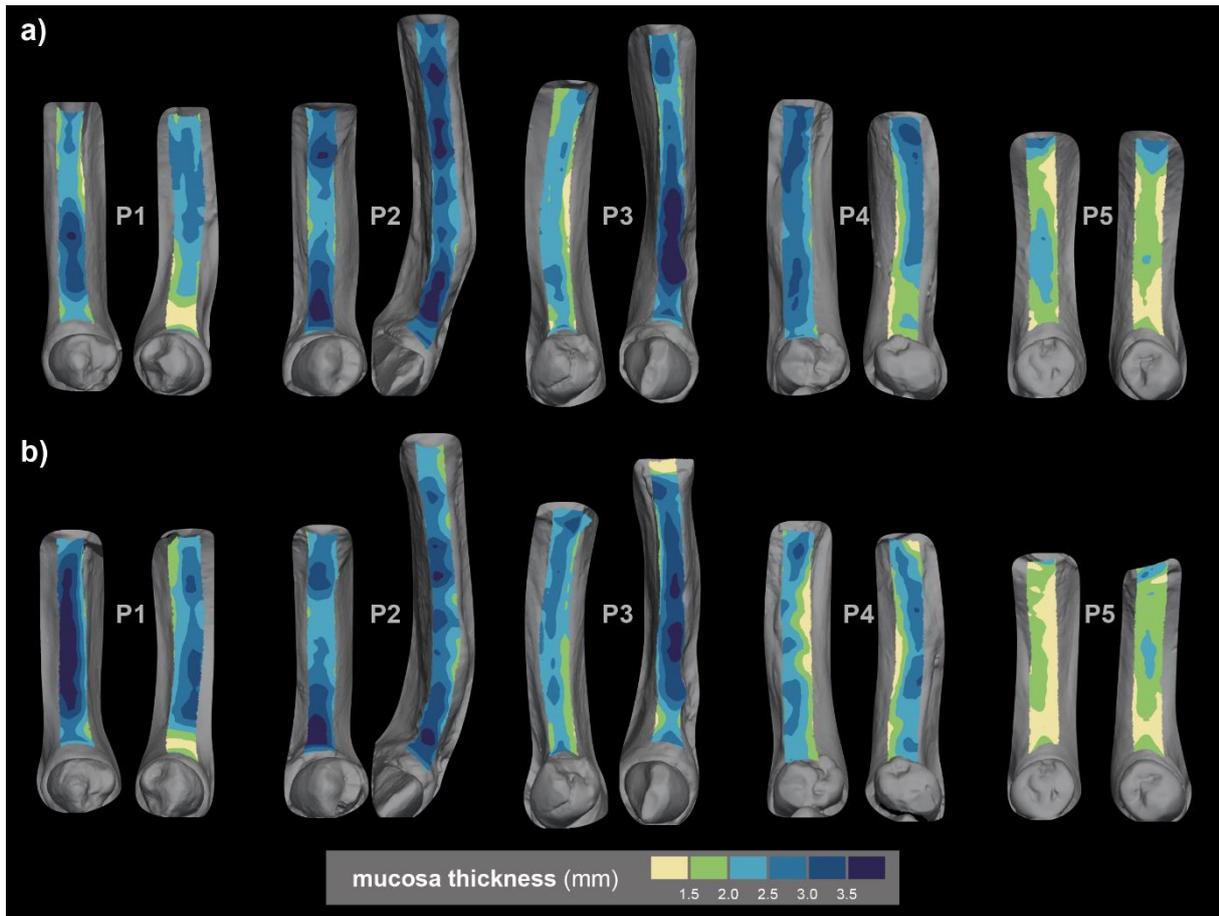
Fig. 5. *Baseline (a) and follow-up mucosa thickness (b) were visualised on the right and left residual ridges for all patients included in the present study.*
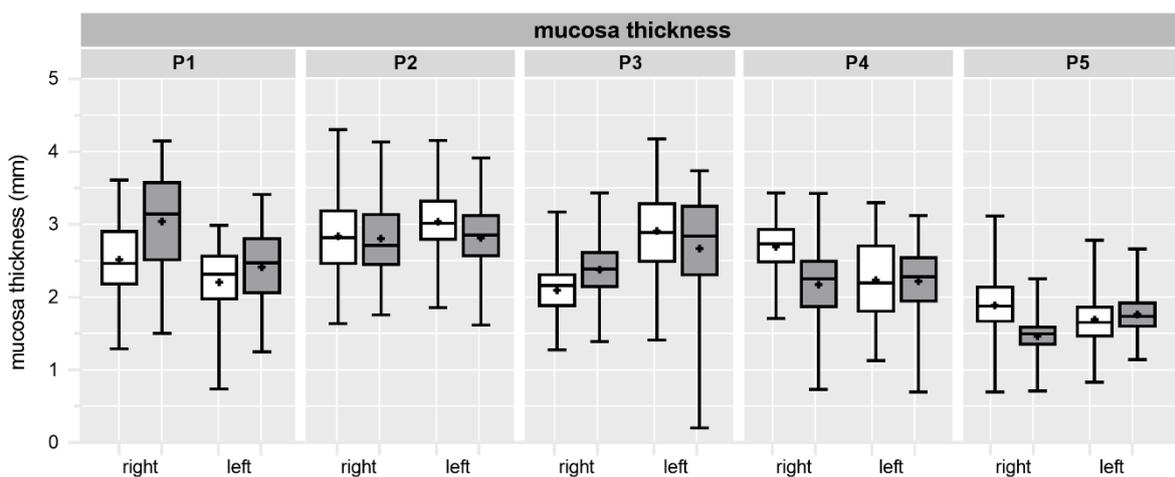

Fig. 6: *Distribution of baseline (white) and follow-up mucosa thickness (grey) of the right and left residual ridges for all patients (P) included in the present study were displayed with boxplots.*

By combining multi-modal and temporal images, mucosa thickness and thickness changes were evaluated. Adding the time component into the virtual patient concept by translating findings from research to the clinic setting also presents a future step towards personalised or precision dentistry (Joda *et al.*, 2020; Lahoud *et al.*, 2022; Schwendicke & Krois, 2022). Furthermore, with AI-assisted segmentation of the CBCT images, segmentation became simpler, increasing future possibilities (Fontenele *et al.*, 2022; Shaheen *et al.*, 2021). Superimposition also presents a crucial step in defining the accuracy of the subsequent analysis (Flügge *et al.*, 2017; Kuralt & Fidler, 2021). With careful selection of stable and unchanged regions, i.e., teeth for CBCT and optical scan alignment and anatomical structures for multitemporal CBCT alignment, the error of the evaluation method is minimised (Kuralt *et al.*, 2019).

To our knowledge, this was the first study to three-dimensionally evaluate and visualise oral mucosa changes associated with wearing a denture independent of bone changes. Recently, there has been renewed interest in the biomechanics of the denture supporting tissues, clinically and theoretically (Chen *et al.*, 2015). In the past, the predominant topic of interest was bone changes of the residual ridge, but recently understanding of the mucosal response has gained interest. With optical scanning alone, mucosa surface change (dSurface) is obtained, representing a mismatch between the intaglio surface of the denture and the denture supporting tissues, which leads to uneven distribution of occlusal forces and overstressing the abutment teeth (Saito *et al.*, 2002). However, dSurface is a combination of bone and mucosa changes of the residual ridge. Therefore, a multi-modal and temporal approach combing CBCT and optical scanning is required to evaluate these changes. CBCT and optical scanning were already utilised in periodontology and implantology to quantify soft tissue thickness (Couso-Queiruga *et al.*, 2021; Kuralt *et al.*, 2020), exhibiting the highest agreement with histological measurements and highest accuracy to the clinical measurements (Ferry *et al.*, 2022). Nonetheless, evaluating soft tissue changes on the underlying bone, also exhibiting changes, remained problematic. Therefore, the novel method also presents an unexploited possibility for soft tissue evaluation in other fields, i.e. periodontology and implantology, for instance a correlation between mucosal thickness changes and periodontal phenotype, i.e. gingival thickness and keratinized tissue width, and bone morphotype (Cortellini & Bissada, 2018; Kim *et al.*, 2020).

Three-dimensional evaluation and visualisation of the denture supporting tissues revealed complex surface, bone, and mucosa dynamics. The previous findings with mucosa exhibiting complex nonlinear and time-dependent behaviours were confirmed in the present study. Bone changes exhibited around half a millimetre thickness loss predominantly of local nature except for the first patient displaying bone loss up to two millimetres. Large differences were also observed between the left and right residual ridge. Mucosa exhibited even higher local variability with both increasing and decreasing thickness. In this regard, mucosal compensatory effects were observed with increased mucosa thickness in large bone loss areas and decreased mucosa thickness in areas without bone changes. Such detailed evaluation would also greatly aid the planning and designing of RPDs to enable successful treatment outcomes in the future.

The present study was subjected to some limitations. First, despite reduced ionising radiation compared to medical computed tomography, CBCT imaging still presents a significant radiation dose to the patient (Jacobs *et al.*, 2018). Therefore, the use of either novel low-dose protocols using CBCT (Yeung *et al.*, 2019) or other non-invasive modalities, such as magnetic resonance imaging (MRI) (Heil *et al.*, 2018), should be assessed further in this regard. Nonetheless, the proposed method can be utilised on surface meshes disregarding the acquisition modality.

CONCLUSIONS

The present study proposed a novel method for precise evaluation and visualisation of mucosa thickness changes resulting from the acquisition of underlying bone changes and mucosa surface changes.

ACKNOWLEDGEMENT

REFERENCES

Ahmad R, Abu-Hassan MI, Li Q, Swain MV (2013). Three dimensional quantification of mandibular bone remodeling using standard tessellation language registration based superimposition. Clin Oral Implan Res 24:1273–9.

Alammar A, Kois JC, Revilla-León M, Att W (2022). Additive Manufacturing Technologies: Current Status and Future Perspectives. J Prosthodont 31:4–12.

Benso B, Kovalik AC, Jorge JH, Campanha NH (2013). Failures in the rehabilitation treatment with removable partial dentures. Acta Odontol Scand 71:1351–5.

Blum IR, Fraser McCord J (2004). A clinical investigation of the morphological changes in the posterior mandible when implant-retained overdentures are used. Clin Oral Implan Res 15:700–8.

Campbell SD, Cooper L, Craddock H, Hyde TP, Nattress B, Pavitt SH, Seymour DW (2017). Removable partial dentures: The clinical need for innovation. J Prosthet Dent 118:273–80.

Chen J, Ahmad R, Li W, Swain M, & Li, Q (2015). Biomechanics of oral mucosa. J Roy Soc Interface 12:20150325.

Cook RJ (1991). Response of the oral mucosa to denture wearing. J Dent 19:135–47.

Cortellini P, Bissada N F (2018). Mucogingival conditions in the natural dentition: Narrative review, case definitions, and diagnostic considerations. J Clin Periodontol 45:S190–8.

Couso-Queiruga E, Tattan M, Ahmad U, Barwacz C, Gonzalez-Martin O, Avila-Ortiz G (2021). Assessment of gingival thickness using digital file superimposition versus direct clinical measurements. Clin Oral Invest 25:2353–61.

Crameri F, Shephard GE, Heron PJ (2020). The misuse of colour in science communication. Nat Commun 11:1–10.

Dong J, Zhang FY, Wu GH, Zhang W, Yin J (2015). Measurement of mucosal thickness in denture-bearing area of edentulous mandible. Chinese Med J-Peking 128:342–7.

Douglass CW, Watson AJ (2002). Future needs for fixed and removable partial dentures in the United States. J Prosthet Dent 87:9–14.

Ferry K, AlQallaf H, Blanchard S, Dutra V, Lin WS, & Hamada Y (2022). Evaluation of the accuracy of soft tissue thickness measurements with three different methodologies: An in vitro study. J Periodontol.

Flügge T, Derksen W, te Poel J, Hassan B, Nelson K, Wismeijer D (2017). Registration of cone beam computed tomography data and intraoral surface scans – A prerequisite for guided implant surgery with CAD/CAM drilling guides. Clin Oral Implan Res 28:1113–8.

Fontenele RC, Gerhardt MN, Pinto JC, Van Gerven A, Willems H, Jacobs R, Freitas DQ (2022). Influence of dental fillings and tooth type on the performance of a novel artificial intelligence-driven tool for automatic tooth segmentation on CBCT images – A validation study. J Dent 119:104069.

Friedli L, Kloukos D, Kanavakis G, Halazonetis D, Gkantidis N (2020). The effect of threshold level on bone segmentation of cranial base structures from CT and CBCT images. Sci Rep-UK 10:7361.

Gaêta-Araujo H, Alzoubi T, de Faria Vasconcelos K, Orhan K, Pauwels R, Casselman JW, Jacobs,R (2020). Cone beam computed tomography in dentomaxillofacial radiology: a two-decade overview. Dentomaxillofac Rad 49:20200145.

Hassan B, Souza PC, Jacobs R, de Azambuja Berti S,van der Stelt P (2010). Influence of scanning and reconstruction parameters on quality of three-dimensional surface models of the dental arches from cone beam computed tomography. Clin Oral Invest 14:303–10.

Heil A, Schwindling FS, Jelinek C, Fischer M, Prager M, Gonzalez EL, Bendszus M, Heiland S, Hilgenfeld T (2018). Determination of the palatal masticatory mucosa thickness by dental MRI: A prospective study analysing age and gender effects. Dentomaxillofac Rad 47:20170282.

Jacobs R, Salmon B, Codari M, Hassan B, & Bornstein MM (2018). c. BMC Oral Health 18:88.

Joda T, Yeung AWK, Hung K, Zitzmann NU, Bornstein MM (2020). Disruptive Innovation in Dentistry: What It Is and What Could Be Next. J Dent Res 100:448-53.

Khamis Abdel Razek M, Shaaban NA (1978). Histochemical and histopathologic studies of alveolar mucosa under complete dentures. J Prosthet Dent 39:29–36.

Kim DM, Bassir SH, Nguyen TT (2020). Effect of gingival phenotype on the maintenance of periodontal health: An American Academy of Periodontology best evidence review. J Periodontol 91:311–38.

Kumar L (2014). Biomechanics and clinical implications of complete edentulous state. J Clin Gerontol Geriatr 5:101–4.

Kuralt M, Gašperšič R, Fidler A (2020). 3D computer-aided treatment planning in periodontology: A novel approach for evaluation and visualization of soft tissue thickness. J Esthet Restor Dent 32:457–62.

Kuralt M, Fidler A (2021). Assessment of reference areas for superimposition of serial 3D models of patients with advanced periodontitis for volumetric soft tissue evaluation. J Clin Periodontol 48:765–73.

Kuralt M, Selmani Bukleta M, Kuhar M, Fidler, A (2019). Bone and soft tissue changes associated with a removable partial denture. A novel method with a fusion of CBCT and optical 3D images. Comput Biol Med 108:78–84.

Lahoud P, Jacobs R, Boisse P, EzEldeen M, Ducret M, & Richert R (2022). Precision medicine using patient-specific modelling: state of the art and perspectives in dental practice. Clin Oral Invest 26:5117-28.

Mangano C, Luongo F, Migliario M, Mortellaro C, Mangano FG (2018). Combining intraoral scans, cone beam computed tomography and face scans: The virtual patient. J Craniofac Surg 29:2241–6.

Mangano F, Gandolfi A, Luongo G, Logozzo S (2017). Intraoral scanners in dentistry: A review of the current literature. BMC Oral Health 17:1–11.

Najeeb S, Zafar MS, Khurshid Z, Siddiqui F (2016). Applications of polyetheretherketone (PEEK) in oral implantology and prosthodontics. J Prosthodont Res 60:12–9.

Ozan O, Orhan K, Aksoy S, Icen M, Bilecenoglu B, Sakul BU (2013). The Effect of Removable Partial Dentures on Alveolar Bone Resorption: A Retrospective Study with Cone-Beam Computed Tomography. J Prosthodont 22:42–8.

Pauwels R, Jacobs R, Singer SR, Mupparapu M (2015). CBCT-based bone quality assessment: are Hounsfield units applicable? Dentomaxillofac Rad 44:20140238.

Piedra-Cascón W, Krishnamurthy VR, Att W, Revilla-León M (2021). 3D printing parameters, supporting structures, slicing, and post-processing procedures of vat-polymerization additive manufacturing technologies: A narrative review. J Dent 109:103630.

Preshaw PM, Walls AWG, Jakubovics NS, Moynihan PJ, Jepson NJA, Loewy Z (2011). Association of removable partial denture use with oral and systemic health. J Dent 39:711–9.

Ramsay SE, Whincup PH, Watt RG, Tsakos G, Papacosta AO, Lennon LT, Wannamethee SG (2015). Burden of poor oral health in older age: Findings from a population-based study of older British men. BMJ Open 5:e009476.

Revilla-León M, Sadeghpour M, Özcan M (2020). A Review of the Applications of Additive Manufacturing Technologies Used to Fabricate Metals in Implant Dentistry. J Prosthodont 29:579–93.

Saito M, Notani K, Miura Y, Kawasaki T (2002). Complications and failures in removable partial dentures: A clinical evaluation. J Oral Rehabil, 29:627–33.

Schulze R, Heil U, Groß D, Bruellmann DD, Dranischnikow E, Schwanecke U, Schoemer E (2011). Artefacts in CBCT: A review. In Dentomaxillofac Rad 40:265–73.

Schwendicke F, Krois J (2022). Precision dentistry—what it is, where it fails (yet), and how to get there. Clin Oral Invest 26:3395–403.

Shaheen E, Leite A, Alqahtani KA, Smolders A, Van Gerven A, Willems H, Jacobs R (2021). A novel deep learning system for multi-class tooth segmentation and classification on cone beam computed tomography. A validation study: Deep learning for teeth segmentation and classification. J Dent 115:103865.

Shujaat S, Bornstein MM, Price JB, Jacobs R (2021). Integration of imaging modalities in digital dental workflows - possibilities, limitations, and potential future developments. Dentomaxillofac Rad 50:20210268.

Srinivasan M, Kalberer N, Fankhauser N, Naharro M, Maniewicz S, Müller F (2021). CAD-CAM complete removable dental prostheses: A double-blind, randomized, crossover clinical trial evaluating milled and 3D-printed dentures. J Dent 115:103842.

Srinivasan M, Kalberer N, Kamnoedboon P, Mekki M, Durual S, Özcan M, Müller F (2021). CAD-CAM complete denture resins: an evaluation of biocompatibility, mechanical properties, and surface characteristics. J Dent 114:103785.

Tallgren A (2003). The continuing reduction of the residual alveolar ridges in complete denture wearers: A mixed-longitudinal study covering 25 years. J Prosthet Dent 89:427–35.

Thiery G, Lazzari V, Ramdarshan A, Guy F (2017). Beyond the map: Enamel distribution characterized from 3D dental topography. Front Physiol 8:524.

Unkovskiy A, Unkovskiy N, Spintzyk S (2021). A virtual patient concept for esthetic and functional rehabilitation in a fully digital workflow. Int J Comput Dent 24:405–17.

Verhelst PJ, Smolders A, Beznik T, Meewis J, Vandemeulebroucke A, Shaheen E, Van Gerven A, Willems H, Politis C, Jacobs R (2021). Layered deep learning for automatic mandibular segmentation in cone-beam computed tomography. J Dent 114:103786.

Yeung AWK, Jacobs R, Bornstein MM (2019). Novel low-dose protocols using cone beam computed tomography in dental medicine: a review focusing on indications, limitations, and future possibilities. Clin Oral Invest 23:2573–81.

Żmudzki J, Chladek G, Kasperski J (2015). Biomechanical factors related to occlusal load transfer in removable complete dentures. Biomech Model Mechan 14:679–91.