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Three-dimensional analysis of aligner gaps and thickness distributions using advanced laboratory-based hard X-ray tomography

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ABSTRACT

The morphology of a polymer aligner, designed according to the orthodontic treatment plan, determines the clinical outcome. A fundamental element of orthodontic tooth movement with aligner treatment is the fit of the aligner surface to the individual teeth. Gaps between aligner and teeth do occur because the current aligner fabrication hardly reproduces the complex anatomy of the individual denture. Our study aims at the quantitative three-dimensional assessment of the fit between optically transparent aligners placed on a polymeric model of the upper dental arch. Using an intraoral scan of a subject's upper dental arch, a model was printed by means of a stereolithographic system. A series of eight Naturaligners® was manufactured with a pressure molding process using thermofoils with thicknesses of 550 and 750 µm and preselected process temperatures between 110 and 210 °C. These aligners placed on the model were imaged by an advanced micro computed tomography system. The aligners were segmented to extract the gaps and their local thicknesses as the function of the processing temperature for the two foil thicknesses. The results indicate that the aligners show a better fit when the foils are processed at higher temperatures. Nevertheless, the processing temperatures can be restricted, as the gain become weaker and weaker. The thermal processing reduces the average thickness of the aligners by 60 % with respect to the planar starting foil. The thickness distributions clearly demonstrate that the aligners are generally thicker on the occlusal surfaces of molars and premolars but thinner around the incisors and buccal as well as oral surfaces. This phenomenon is most welcome because bruxism leads to abrasion. The NaturAligner®'s surface layer consists of cellulose, thus the microplastics are expected to be substantially less critical.

Keywords: Optically transparent aligner, advanced high-resolution tomography, aligner gap, aligner thickness distribution, three-dimensional registration, segmentation

1. INTRODUCTION

Orthodontic treatments with optically transparent aligners have seen a constant increase in acceptance in recent years. The low acceptance rates of conventional orthodontic devices in adult populations, due to a perceived lack of attractiveness, as well as workflows becoming easier for the practitioners can explain the rising demand for aligner treatments [1, 2]. Orthodontic tooth movement is accomplished by employing prolonged pressure on that tooth. The initial movement is rapid as it occurs within the dental alveolus. Periodontal ligaments (PDL), which connect the tooth to the alveolar bone, are stretched and compressed on each side of the root so that a tension and a compression side can be differentiated [3]. When the mechanical balance of the PDL and bone is disrupted through orthodontic forces, specialized cells are recruited in the vicinity of the tooth [4]. The compression of ligaments leads to a reduction of blood flow which ultimately causes a focal necrosis. The result is an inflammatory response where osteoclasts appear at the compression side to resorb necrotic PDLs and adjacent bone [5].

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Tooth movement is delayed until this biological response starts [5]. On the tension side, osteoblasts are recruited as the PDL is stretched. Once they start the apposition of new bone, the tooth moves more rapidly again. This process called bone remodeling usually occurs within forty days after the initial force is applied [3]. Aligners are used for treating mild to moderate and some complex malocclusions [6]. In comparison with conventional orthodontic appliances, clear aligners are known to cause limited negative periodontal effects as they can be removed before cleaning one's teeth [7] and cause limited clinical emergencies as they can be easily replaced if broken or lost [8]. The rapid advancement of digital technologies in dentistry and in the field of orthodontics has led most aligner manufacturing companies to go for a complete digital workflow. As intraoral scanners have become more accurate [9] and easier to handle, more practitioners were able to offer aligner treatments to their patients. Such a treatment normally starts with an intraoral scan of the upper and lower dental arch, and generated data is then processed using computer-aided design (CAD) to create virtual 3D models. A treatment-planning program enables practitioners to virtually move the teeth in the desired position in steps that should range from 0.2 to 0.5 mm [10]. For each step, a 3D model is created and printed using a stereolithographic technique (3D printer). These models are then used to create aligners with a thermoforming procedure using a polymer foil. Depending on the phase of the treatment, aligners of specific thicknesses can be used to modulate the force being applied to the tooth [11]. This choice is of importance as excessive forces can cause hyalinization, bone necrosis and external root resorption [12]. Depending on the severity of the malocclusion, treatments last from four to 18 months [8]. The success of aligner treatments depends on multiple factors ranging from the precision of the intraoral scanners, 3D models [6], thickness and stiffness of the aligners [13, 14], and fit on the dental arches, see Figure 1.

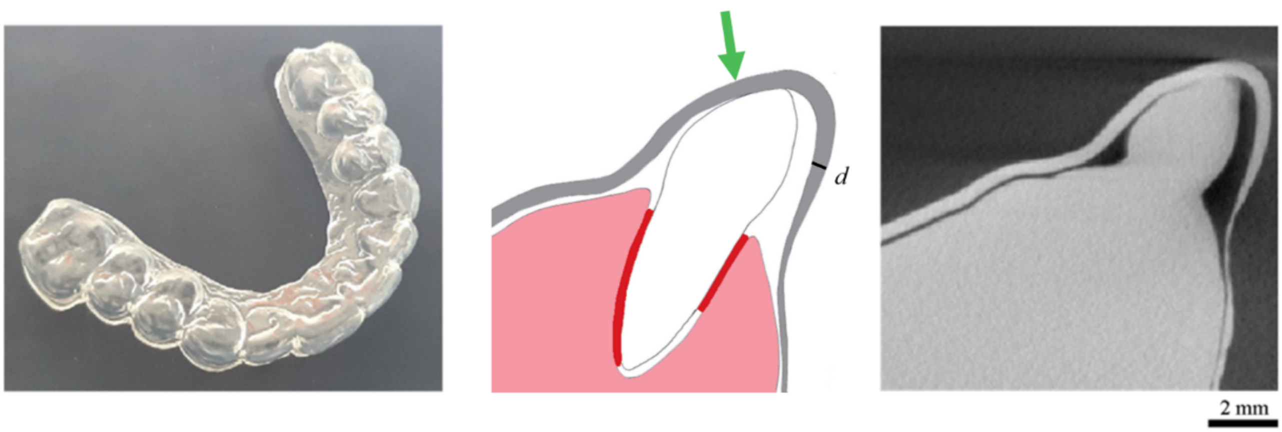

Figure 1. An optically transparent aligner is a thermally processes polymer foil, which should fit the complex human dentition, see left image. Following the planning, the foil should generate force and momentum on the teeth to be moved, see scheme. Red-colored lines show the area of compression due to the force indicated by the green-colored arrow. The fit is critical, as gaps prevent the force transmission. The amplitude of the force transmission correlates with the gray aligner thickness *d*. Therefore, the present tomography study aims at the measurement of local thicknesses and the identification of gaps, clearly visible in the tomographic slice of an aligner suboptimal for orthodontic treatments, see right image.

Several polymeric materials are commercially available on the market. Many of them, however, release microplastics or even cytotoxic components. The recently introduced NaturAligner® (Bottmedical AG, Basel, Switzerland), which comes in two thicknesses, i.e. 550 µm, denoted NA.550, and 750 µm, denoted NA.750, is prepared from a bio-based material that avoids the exposure to conventional microplastics during treatment. Research on the interaction between microplastics and human body is still ongoing, and long-term effects are thus only partly understood [15]. Nevertheless, health hazards caused by immunological disturbances and chemical toxicity are being discussed as well as their risks for cancer [16, 17]. Therefore, it raises concerns about the effect of wearing aligners on patient's health as they should be worn for 22 hours a day for a total period up to 18 months depending on the treatment plan. The NaturAligner® has a biopolymer coating based on cellulose which separates the force-generating polymer from the oral mucosa thus preventing exposure. The current study is based on morphology measurements of the aligners using micro computed tomography. These 3D datasets were quantitatively analyzed to determine the gap volumes and the local thickness changes as the result of the thermoforming process. These results support the engineer's work in defining the parameters relevant for aligner production.

2. METHODOLOGY

2.1 Aligner fabrication

The upper jaw of the subject was scanned using the intraoral scanner Medit i500 (Medit corp., Seongbuk-gu, South Korea). The generated data were converted into the Standard Tessellation Language (STL) format and processed using computer-aided design (Medit Link, Medit corp., Seongbuk-gu South Korea) and a triangle-mesh software (Meshmixer, Autodesk Inc., San Rafael, USA). Artifacts caused by the scanning process were removed and the edges of the model were smoothened to add a base to the models so that there is sufficient mechanical stability during the thermoforming process. Eight copies of the model were printed using the stereolithographic printer Formlabs Form3 (Formlabs, Somerville MA, USA) on the basis of the photopolymer resin Grey V4. All models were printed in 407 layers measuring 50 µm each, washed with isopropyl alcohol to remove residual liquid resin and post-cured with UV-light at a wavelength of 405 nm for a period of 15 minutes at a temperature of 60 °C. This last step enhanced the mechanical properties by terminating the polymerization. A series of eight NaturAligner® were thermoformed on the dental models with a pressure molding device (Biostar, Scheu-Dental, Iserlohn, Germany). The process started by placing the foil in the holder and heating it using an infrared heater. A thermometer probe was placed right under the foil and once the desired temperature was reached, the foil was positioned over the model and molded in the integrated pressure chamber by applying air pressure of 5.8 bar. After a cooling period of one minute, the aligners were cut at the lower edge of the models but not dismounted. Each aligner had specific properties as the two foil thicknesses of 550 and 750 µm were used. The heating temperatures ranged from 112 to 201 °C.

2.2 Tomographic imaging

NaturAligner® specimens and the resin-based models exhibited similar local X-ray absorption values. Therefore, a simple intensity-based segmentation procedure could not be applied. Another challenge was the potential plastic deformation of the aligners as the result from the removal of the models. The scanning protocol was optimized to represent the aligner properly and to rule out mechanical damages. For each set of aligner and model, two sets of tomographic data were acquired: aligner mounted on the model (model+aligner) and model without aligner (model). The models were fixed on a holder, allowing to scan them in the same position during both scans. Subsequently, the corresponding model+aligner and model images were three-dimensionally registered. The tomographic data acquisition was performed with the nanotom m (phoenix|x-ray, GE Sensing & Inspection Technologies GmbH, Wunstorf, Germany). It is equipped with a nanofocus tube, which allows for a maximal acceleration voltage of 180 kV and can generate a power up to 15 W. In our case, we employed an acceleration voltage of 90 kVp and a beam current of 200 µA. The effective pixel length was set to 33 µm and the mean photon energy was increased by implementing a 0.5 mm-thick aluminum film behind the transmission target. A set of 2,000 radiographs were taken along 360° with an exposure time of two seconds per projection. The scan duration was therefore approximately 67 minutes.

2.3 Aligner thickness measurements

The bottom region of the model+aligner and model image were registered and evaluated with the open-source software Elastix (https://elastix.lumc.nl) [18]. As the resin-based models and the aligners had similar local X-ray absorption values, the aligner thickness was determined by subtracting the registered model from the model+aligner images. The resulting aligner mask was extracted via automatic thresholding using Otsu's method, keeping the largest connected component and applying morphological image closing. By extracting two-dimensional centerline masks from all slices in the three orthogonal directions and keeping centerline voxels which exist in more than one direction, the final center-surface were determined. They were then used as reference points to measure the thickness by calculating the distance to the nearest boundary point and multiplying it by a factor of two. This method was validated using the visualization program VGStudio Max 2.1 (Volume Graphics, Heidelberg, Germany). Two reference aligners, *i.e.* NA.550 processed at a temperature of 142 °C and NA.750 processed at a temperature of 143 °C, were chosen, and a total of ten positions were randomly selected for a semi-automatic thickness measurement. By applying an automated threshold and the function 'surface determination', defining the boundary between an object and its background based on their density, we were able to display the border of the aligner in an automated and reproducible way. The distance between the borders of the aligner was then determined using a digital measuring tool.

2.4 Gap volume determination

The gaps between aligners and models were extracted from the model+aligner images which was based on thresholding the images with a fixed threshold, resulting in binary masks. Three morphological image operations were employed to fill the gaps in each mask: first dilation by a sphere of radius R, then filling holes, and at last erosion by a sphere of radius R. Gaps were defined by subtracting the binary masks from the filled masks. To determine the same region of interest, a plane 2 mm below the tooth-gingiva border was defined in the reference model NA.550 processed at a temperature of 200 °C. This plane was transferred to all model+aligner images by image registration. It was used to remove the image content below the plane as well as to seal the model+aligner image to support the hole filling operation for the creation of the filled mask. This method was also validated using VGStudio Max 2.1 (Volume Graphics, Heidelberg, Germany) by segmenting manually all the gaps of the reference model NA.750 at a processing temperature of 176 °C as well as the gap of a region of interest, *i.e.* the buccal gap between the central incisors, for all models. To define this region of interest, all model+aligner images were aligned and cropped by predetermined coordinates. The 'region growing' method was used to semi-automatically segment the gaps, which determines whether a voxel should be included in the segmentation by defining a seed voxel and a suitable threshold.

3. RESULTS

3.1 Validation of automatic measurement

The comparison of manual and automatic thickness measurements is shown in Table 1. With the semi-automatic method, we found a mean thickness of 165 µm for the NA.550 and of 194 µm for the NA.750 aligners at five randomly selected positions each. Using the automatic measurement method, a mean thickness of 162 µm for the NA.550 aligner fabricated with a processing temperature of 142 °C and 168 µm for the NA.750 aligner prepared at a processing temperature of 143 °C was determined for the same positions. The mean absolute difference for the aligner NA.550 was found to be 15 µm, and for the aligner NA.750 it corresponds to 26 µm. Note, the isotropic voxel size for all datasets was 33 µm. The correlation between the two measurement methods was quantified via the Pearson correlation coefficients ρ. They correlate with $\rho = 0.828$ for the NA.550 aligner fabricated with a processing temperature of 142 °C and with $\rho = 0.925$ for the NA.750 aligner prepared at a processing temperature of 143 °C.

Table 1. Comparison of automatic and manual thickness measurements of the aligners NA.550 and NA.750 fabricated at a processing temperature of 142 and 143 °C, respectively. The results were obtained at five arbitrarily selected positions, where the aligner was clearly separated from the model surface.

	NA.550				
automatic [µm]	162	187	114	187	162
manual [µm]	181	166	128	176	172
difference [µm]	-19	21	14	11	-10
	NA.750				
automatic [µm]	187	219	114	187	132
manual [µm]	203	237	148	195	186
difference [µm]	-16	-18	-34	-8	-54

The comparison of the automatic and manual segmentations of gaps also showed consistency, see Table 2. Using a fixed gray-value threshold of 150, a total volume of 24.6 mm³ was determined with the automatic segmentation for all gaps, *i.e.* for the about four dozen gaps along 14 teeth of the selected aligner NA.750 processed at a temperature of 176 °C. The manual segmentation of the same aligner resulted in a total volume of 29.4 mm³. The difference between the two methods was found to be 4.8 mm³, see last column of Table 2.

The results of the segmentation of the buccal gap between the central incisors for all aligners are shown in the columns headed by ROI. The mean gap volume for the automatic segmentation totaled 8.9 mm³ for the NA.550 and 5.5 mm³ for the thicker NA.750 aligners. Also employing the fixed gray-value threshold of 150 as starting value for the manual segmentation, we found mean gap volumes of 8.7 mm³ for the NA.550 and 5.6 mm³ for the NA.750 aligners. The mean absolute difference between automatic and manual procedures was 0.6 mm³ for the NA.550 and 0.3 mm³ for the NA.750 aligners. The related Pearson correlation coefficients corresponded to 1.000 and 0.998, respectively. Taking the correlation coefficients and mean absolute difference values into consideration, we could validate the reliability of the automatic gap volume and aligner thickness measurement methods.

Table 2. Automatic determination of the volume of one selected gap (ROI), the buccal gap between the central incisors, and total gap volume (all gaps) in comparison to the manual segmentation.

	ROI								all gaps
aligner	**NA.550**				**NA.750**				**NA.750**
process temperature [°C]	112	142	173	200	112	143	176	201	176
automatic [mm³]	24.8	6.9	1.7	2.2	16.7	2.2	2.0	1.2	24.6
manual [mm³]	25.4	7.0	1.0	1.3	16.4	2.9	1.7	1.3	29.4
difference [mm³]	-0.6	-0.1	0.7	0.9	0.3	-0.7	0.3	0.1	-4.8

3.2 Aligner thickness distribution

The results of the local aligner thickness measurements are listed in Table 3. Using the automatic measurement method, the following median aligner thicknesses were determined for all center-surface voxels. For the NA.550 aligners, the median thickness was 361 µm using a processing temperature of 112 °C, 337 µm using a processing temperature of 142 °C, 330 µm using a processing temperature of 173 °C, and 330 µm using a processing temperature of 200 °C. Concerning the NA.750 aligners we found 462 µm using a processing temperature of 112 °C, 428 µm using a processing temperature of 143 °C, 443 µm using a processing temperature of 176 °C, and 448 µm using a processing temperature of 201 °C. The overall thickness of the aligners was, therefore, almost constant in the temperature range studied, but substantially smaller than the thickness of the planar foils employed as starting material in the thermoforming process.

Table 3. Summary statistics of thickness distribution values for the entire datasets and for 100 randomly selected voxels on center-surface.

	NA.550				**NA.750**			
process temperature [°C]	112	142	173	200	112	143	176	201
all data used								
minimum [µm]	66	66	66	66	66	66	66	66
median [µm]	361	337	330	330	462	428	443	448
mean [µm]	336	330	329	320	440	427	429	430
maximum [µm]	594	579	676	689	761	888	919	956
standard deviation	99	74	73	79	87	96	114	154
100 data points								
minimum [µm]	66	162	93	66	187	148	66	66
median [µm]	373	337	337	330	462	438	435	485
mean [µm]	338	339	338	321	447	436	427	455
maximum [µm]	485	480	528	568	583	590	660	717
standard deviation	97	62	64	97	81	82	113	152

As the number of center-surface voxels averaged three million per aligner, we provide a simplified representation of the results in Figure 2. The diagram shows the mean thickness when sampling 100 random points for 100 times. The values were relatively stable to resampling, thus allowing a reasonable approximation. The NA.550 foils were on average 339.5 µm thick. The NA.750 foils resulted in a thickness of 445.25 µm after the thermoforming process. These results demonstrate a shrinkage of 60.1 % and 59.3 % for the NA.550 and NA.750 aligners, respectively.

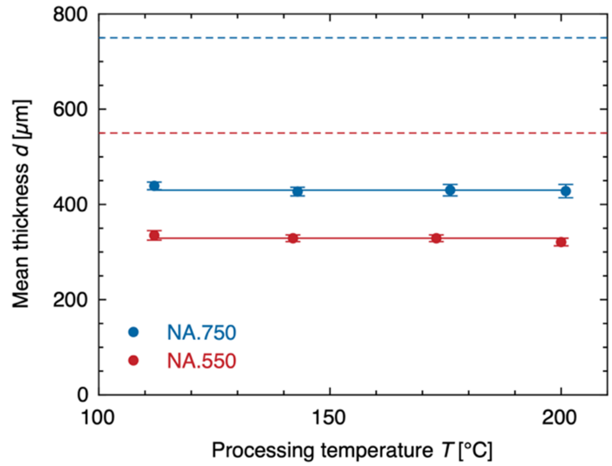

Figure 2. Thickness distribution of the mean when sampling 100 times 100 center-surface voxels, with solid lines showing the average value. The dashed lines show the thickness of the foils before thermoforming.

Although the mean and median thickness values were stable, there was a difference in the thickness distribution after the thermoforming process. The maximum intensity projections, represented in Figure 3, show the thickness distribution of the mounted aligners in three-dimensional space. The NA.550 aligners were generally thicker on the occlusal surfaces of molars and premolars but thinner around the incisors and buccal as well as oral surfaces. Although the NA.550 produced at a processing temperature of 112 °C was slightly thicker on said zones when compared to other NA.550 aligners, the thickness distribution was fairly even across the selected temperature range. This behavior indicated that the NA.550 aligner was hardly affected by changes in selected processing temperatures and thus stable to the thermoforming process. The NA.750 aligners, however, showed noticeable differences when exposed to rising process temperatures. Visible changes occurred between 143 and 173 °C and were accentuated using processing temperatures of 201 °C. Similar to its thinner counterpart, NA.750 foils were thicker on the occlusal surfaces of molars and premolars. But changes became clearer with rising temperatures as the foils got thicker on the palatal surface of all front teeth as well as on the palate itself. Therefore, we have been able to conclude that the selected temperature of thermoforming process has an impact on the thickness distribution of NA.750 foils contrary to the NA.550 ones.

3.3 Gap volume

The results of the gap segmentations are shown in Figure 4. Selecting the proper threshold was critical, as taking inappropriate values resulted in inaccurate segmentations. As the foils completely thinned out in some areas, there was no optimal threshold for segmenting all gaps perfectly well. Therefore, using the automatic segmentation method as mentioned above, we measured the gaps of each aligner with three thresholds, namely 140, 150, and 160 and calculated the average for each processing temperature and aligner thickness. Thermoforming the aligners on the corresponding models resulted in the following mean gap volumes: 268.9 mm³ for the processing temperature of 112 °C, 115.3 mm³ for the processing temperature of 142 °C, 21.9 mm³ for the processing temperature of 173 °C, and 11.2 mm³ for the processing temperature of 200 °C using the NA.550 foils. Using the thicker foils NA.750, we found 191.1 mm³ for the processing temperature of 112 °C, 26.3 mm³ for the processing temperature of 143 °C, 24.8 mm³ for the processing temperature of 176 °C, and 15.72 mm³ for the processing temperature of 201 °C. Using the thermoforming temperature of 112 °C, the NA.750 had a mean gap volume about 30 % smaller than the one of NA.550, see Figure 4. Increasing the temperature in steps of about 30 K, one recognizes a reduction in the total gap volume for both foil thicknesses. The data of the NA.550 displayed in the diagram of Figure 4 correspond to a percentual volume decrease of 57 %, 35 %, and 4 %, respectively per increasing process temperature steps. The aligners made with the 750 µm-thick foil were decreased by 86 %, 1 %, and 5 %, respectively, for the individual 30 K process temperature steps.

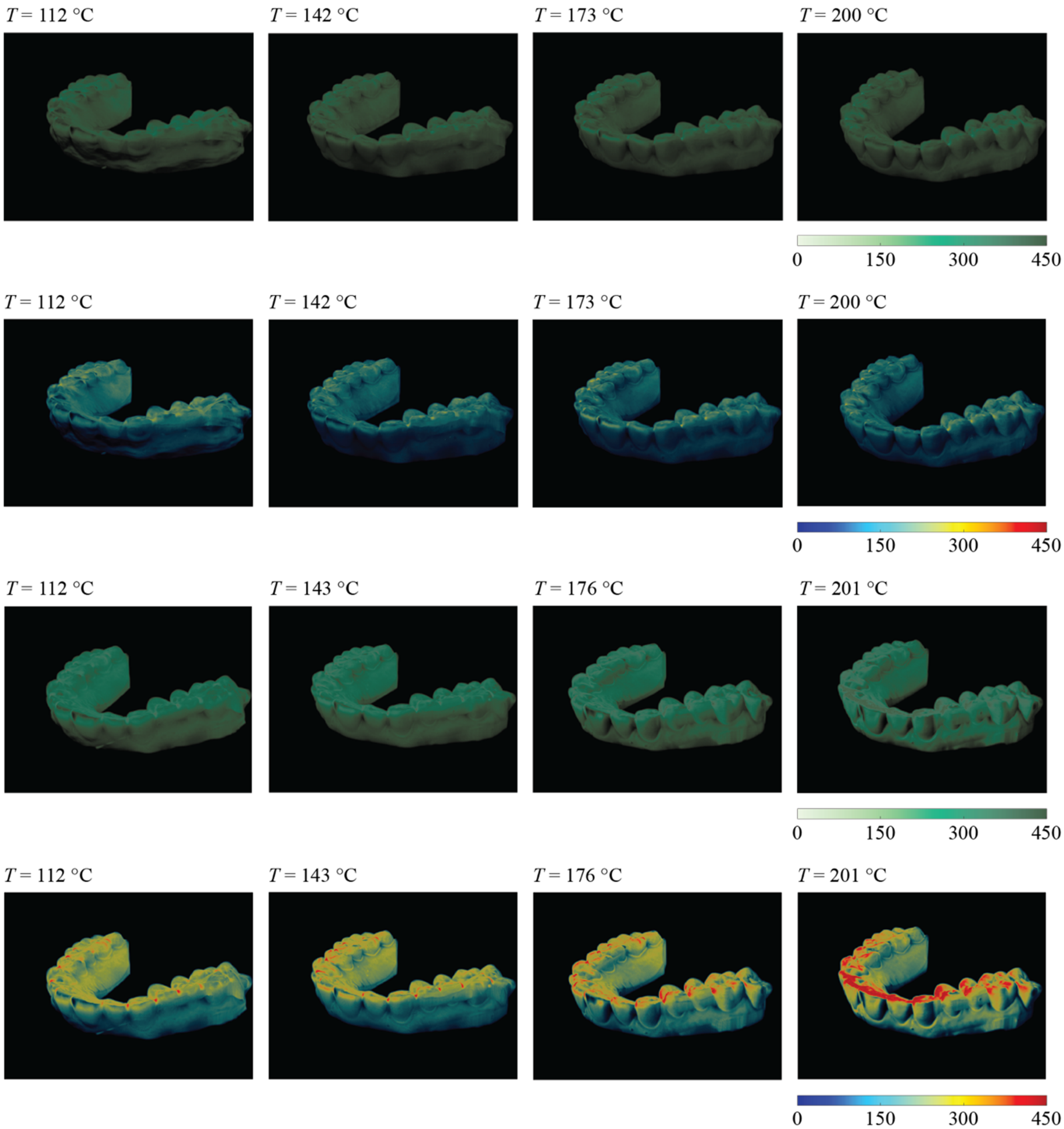

Figure 3. Color-coded aligner thickness distribution for the aligners NA.550, rows 1 and 2, and NA.750, rows 3 and 4. The color bars show the thickness in µm. The processing temperatures during the thermoforming are given as well.

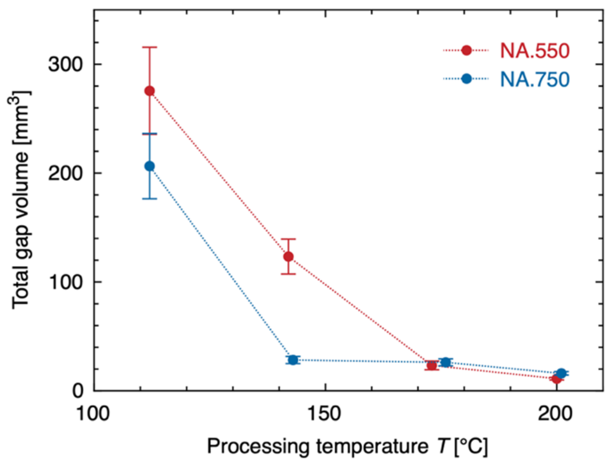

Figure 4. Total volume statistics for all gaps derived from the automatic method. The error bars were determined by using the three threshold values 140, 150, and 160. The dotted lines, which connect the data, should just guide the eyes.

The rendering of Figure 5 shows the gap size distribution for the selected process temperatures. It is distinctly visible that the areas, where gaps form throughout the selected temperature range, are between the teeth and at the tooth-gum border. At low processing temperatures, areas around the palate also show larger gaps. The buccal and palatal tooth surfaces show no visible gaps at higher processing temperatures. This experimental result is of importance as those surfaces are central to orthodontic tooth movements. We can, therefore, conclude that aligners made with NA.750 foils have smaller gaps and a rise in temperature affects the gap volume more drastically than for NA.550 foils. Although the difference becomes negligible at higher processing temperatures, the gaps seem to be inevitable due to the morphology of teeth.

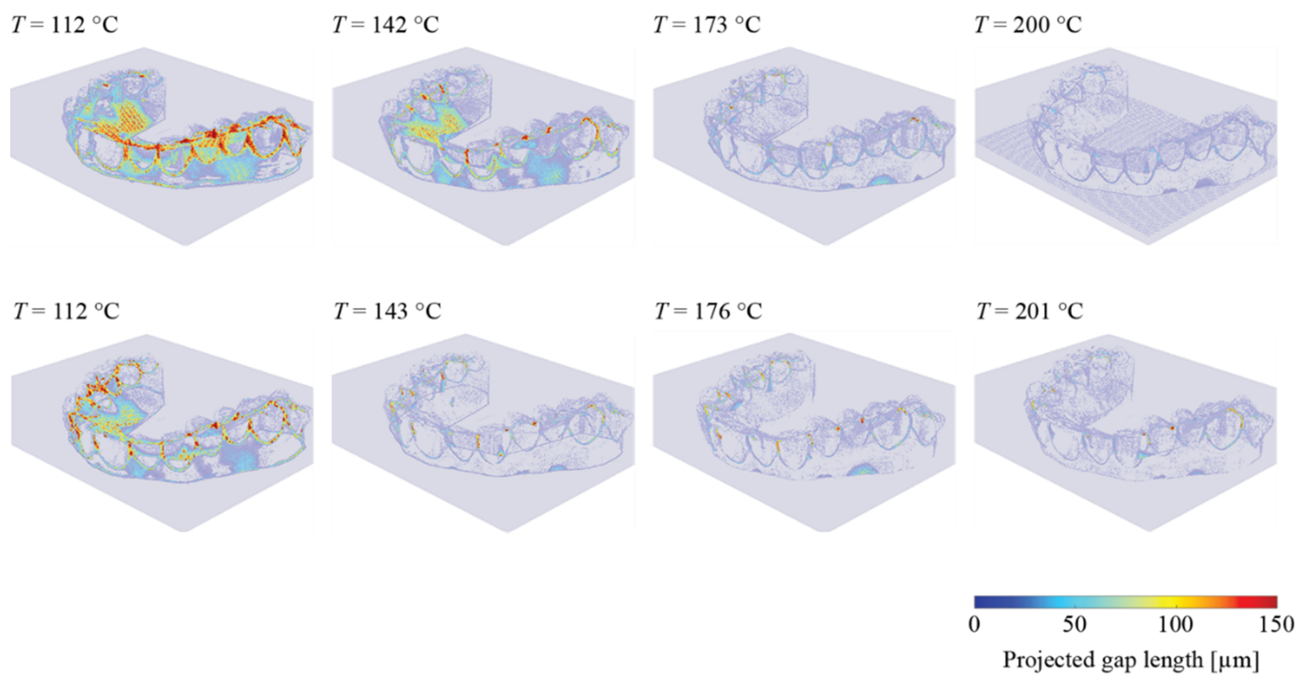

Figure 5. Rendering of projected gap lengths for the NA.550 aligners, top raw, and NA.750 aligners, bottom raw. The selected processing temperatures are indicated.

4. DISCUSSIONS

4.1 Clinical perspective

In patients undergoing orthodontic treatment using aligners, the vast majority of the orthodontic tooth movement, during any two-week aligner prescription cycle, occurs during the first week of the cycle. This varied tooth movement is due to the type of material, thickness and gap volume. The most common approaches for aligner treatment are (i) implementing smaller tooth movements in each setup, which results in more treatment steps, or (ii) using thinner and less stiff aligners while maintaining the tooth movement recommendation of 0.2 to 0.5 mm. In our study, however, we explored an alternative approach based on the thickness of the foils to negate factors such gap volumes and intensity of forces. We found that both foil thicknesses can be beneficial to get the best outcomes in an individual patient plan. In the initial phase of an orthodontic treatment, mild forces should be applied to avoid any adverse effects on the teeth and the surrounding tissue by choosing the right aligner stiffness and also take gap volumes into consideration. Choosing an aligner that does not apply too much force on teeth seems therefore central to that matter. While comparing thinner and thicker aligners, a study found that the latter will deliver significantly greater forces [19]. The authors concluded that there was a strong correlation between foil thickness and delivered forces. Thinner foils are more flexible and therefore better suited for the initial phase of an aligner treatment. Once it is over, higher orthodontic forces can be applied by using thicker foils. Practitioners should be aware that the thickness distribution of NA.750 is altered when processing temperatures above 170 °C are employed. They can use this information to take advantage, as higher forces can be applied vertically on upper molars and incisors, making intrusions and protrusions easier.

4.2 Aligner fitting precision

A study investigating aligner fitting accuracy with laboratory-based micro computed tomography, found that six commercially available aligners had a gap volume ranging between 107 and 402 mm^3 in the studied temperature range but with a region of interest that did not include the entirety of teeth [20]. In our study, a plane 2 mm under the lowest tooth-gum border was defined, allowing us to broaden the region of interest to all teeth. Even with a larger region of interest, the NaturAligner® gaps were at least similar or significantly smaller than the six aligner brands included in the study mentioned before. Another important step regarding aligner fitting accuracy during the manufacturing process is the dismounting of the aligner from the models. Using high forces can lead to plastic deformation and thus to permanently damaged aligners. This in return could affect force delivery as they will not properly fit on the dental arch anymore.

4.3 Mechanical properties

The oral cavity forms a particular environment as it is close to body temperature, humid and subject to mechanical as well chemical stress through teeth, saliva, food and beverages. Protocols of many commercially available aligners state that they should be worn 20 to 22 hours a day and changed after one to two weeks. Each aligner is therefore exposed to the conditions of the oral cavity for about 150 to 300 hours. An ideal aligner should be able to exert a constant and equal force over this period of time. It seems therefore important that mechanical properties including stiffness, hardness and elasticity do not significantly change due to intraoral conditions and regular usage. Although it is recommended to study the mechanical properties of thermoplastic foils after the thermoforming process [21], preliminary results show that foils are subject to a substantial stress decrease in the hours following the application of an initial force [22]. Cyclic forces, which emulate forces occurring during chewing and swallowing movements, also appears to have an impact of the delivered forces as mechanical properties are altered [23]. Changes include decreased wear resistance, increased brittleness and stiffness as well as deformation [24, 25]. Also, aligners need to be inserted and removed several times daily before and after meals as well as for oral hygiene. Study conclusions on the effects of removal frequency on deformation and thus force delivery are not unanimous [23, 26]. Although the clinical relevance of the change of mechanical properties has to be demonstrated as most studies have an *in vitro* design, possible differences in force delivery during intraoral use must be taken into consideration when choosing an aligner brand. Our study also falls into this category as all measurements were done on a resin cast. Nevertheless, further research with improved study designs could be conducted to measure the effect of *in vivo* usage of NaturAligner® and the possible consequences on the predictability of an orthodontic treatment.

4.4 Optical properties

The visibility of orthodontic devices can influence the way a person is perceived and may influence a patient's choice of appliance [2]. An aligner's transparency makes it almost invisible; this appears to be a key feature for patients opting for an aligner treatment. But the optical properties of aligners can change over time as the contact with pigments from food and beverages can cause colorations [27, 28]. The outcome of an aligner treatment is heavily influenced by the numbers of hours a patient wears them [3]. Therefore, it seems important that patients do not feel any social discomfort, as it might influence their compliance. For this reason, the stability of optical properties of NaturAligners® should be taken into consideration for further studies.

4.5 Attachments

Certain types of orthodontic movements such as extrusion, mesio-distal root tip and rotation of lateral incisors, canines or first premolars are poorly predictable with aligners. In those cases, auxiliaries called attachments can help make a treatment outcome more predictable. They are made out of composite, fixed on teeth and allow aligners to exert forces in directions, which would be impossible otherwise [6]. Composites are a type of material primarily used for dental fillings. Their mechanical and optical properties depend on their composition. Ones with a high percentage of filler are called bulk-fill and with a low percentage flowable. Considering the fact that an aligner needs to fit the dental arch precisely, it seems evident that it should also do so for attachments. Even though the shape of an attachment and the type of composite seems to play a central role in retention and thus, force delivery, aligners generally fit attachments quite well [29]. Therefore, we can hypothesize that the NaturAligner® does remain similar to other aligners. Nevertheless, further investigation should be conducted to assess the fitting precision of NaturAligner® to such attachments.

5. CONCLUSIONS

Advanced laboratory-based hard X-ray tomography is a reliable method to measure aligner gap volume and thickness distribution. The segmentation procedure is challenging since the X-ray absorption values of the models and aligners were similar. The proposed procedure can be used for any other aligner and similar device. NaturAligner® fit the dental arches with high precision and the selected foil thicknesses make differential orthodontic tooth movements possible. The initial phase of orthodontic treatment can be better accomplished with NA.550 and later phase of tooth movement with NA.750.

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