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Comparison in Accuracy of Orthodontic Retainers Fabricated via Digital Printing Versus Thermoplastic Technique

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ABSTRACT

Introduction: Limited evidence exists on the dimensional accuracy of three-dimensional (3D) printed orthodontic retainers utilizing the newest printing technologies. This study aimed to evaluate the dimensional accuracy of 3D-printed orthodontic retainers in comparison with retainers fabricated from a pressure-form, thermoplastic technique (PFTT).

Methods: Four groups of retainers (n=7 per group) were printed using four printers: Asiga Pro4K80, NextDent 5100, SprintRay ProS, and Formlabs Form3B. The control group (n=7 retainers) was fabricated using PFTT. A polyvinyl siloxane impression of the intaglio surface per retainer was made and optically scanned. Metrology software (Geomagic Control X) was used to digitally superimpose the intaglio surface of each retainer onto the digital master cast using a best-fit algorithm. Surface deviation values (range, root mean square (RMS), and average) between retainers and master casts were calculated and analyzed with analysis of variance and Tukey tests ($\alpha = 0.05$).

Results: For the maximum-to-minimum range of surface deviation, Asiga, NextDent, and SprintRay groups showed significantly more deviation from the master cast than Formlabs and PFTT. Additionally, the Asiga group exhibited significantly higher RMS deviation from the master cast than all other groups. Also, the Asiga and NextDent groups were significantly inclined to have a positive average surface deviation from the master cast than SprintRay, Formlabs, and PFTT groups.

Conclusions: Significant differences in accuracy were found among retainers fabricated from various 3D-printers and a PFTT. Despite these differences, all fabrication methods produced accuracies that were within the clinically acceptable range of 0.25 mm.

DISCLAIMER

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INTRODUCTION

In modern orthodontic practices, additive manufacturing such as three-dimensional (3D) printing is quickly supplanting traditional techniques in dental practices. 3D-printing technology not only simplifies traditional clinical and laboratory techniques, but it also streamlines them into a more automated, digital workflow, allowing same-day turnarounds for timely delivery of restorations and appliances. It improves the overall patient experience, alleviates the discomfort associated with dental impressions, and adapts to the increasing patient demand for clear retainers and aligners over traditional appliances due to their improved esthetics and comfort.[1,2] Because of these benefits, the workflow to fabricate orthodontic appliances is shifting from physical processing to a complete virtual environment. An example of a digital workflow includes: 1) scanning the patient's maxillary and mandibular arches using an intraoral scanner, 2) virtually designing the appliance using computer-aided design (CAD) software, and 3) printing the appliance using additive manufacturing.

Although 3D-printing of retainers offers many advantages over indirect fabrication techniques, digital printing is not free of problems. Similar to the conventional way of retainer fabrication, whereby physical errors are introduced and accrued through the transitional points such as making impressions, pouring stone casts, and thermoforming retainers, errors can also be presented virtually during digital rendering and numerical modeling, through which definition and details are progressively lost at each step of the CAD processing. Finally, the quality and trueness of the fabricated appliance can be impacted by the inherent resolution and accuracy of the scanner and printer. Therefore, quality assurance – and eminently, quality enhancement – of each retainer fabricated via 3D-printing is more important than ever today.

A study by Nasef et al. (2017)[3] compared the dimensional accuracy of the direct, printed retainers to those made by the thermoformed technique. They concluded there was not a statistically significant difference in dimensional accuracy between the printed and thermoformed retainers. In contrast, Cole et al (2019)[4] compared the dimensional accuracy of retainers directly printed from a Form2 (Formlabs) printer to thermoformed retainers made on both stone casts and 3D-printed casts using a PFTT. The study found that 3D-printed retainers were the least accurate but still fell within the 0.5 mm range of clinical acceptability defined in the study.[4] Additionally, other studies have shown that small variations of heat and pressure during the conventional thermoforming process can create discrepancies in the fit of thermoformed retainers and aligners and their physical and mechanical properties.[5-8]

With the advent of new printing technologies, limited evidence exists on the dimensional accuracy of 3D-printed orthodontic retainers utilizing the latest printers. The objective is to evaluate and compare the dimensional accuracy of retainers that are 3D-printed using four novel 3D-printers (Form3B, SprintRay ProS, Asiga Pro 4K80, and NextDent 5100) against retainers that are made using a traditional PFTT.

The null hypothesis is that there will be no difference in the accuracy of retainers fabricated via additive manufacturing (experimental groups) in comparison to retainers fabricated via the pressure-formed, thermoplastic technique (control). Herein, accuracy will be defined by the values of maximum surface deviation, average distance, and root mean square between the intaglio surface of the retainer and the surface of the master cast.

MATERIALS AND METHODS

Study Groups and Design

The study sample investigated 1 control and 4 experimental groups (n = 7 retainers per group). See Figure 1 for experimental design and workflow. Four popular, commercially available printers (1 SLA and 3 DLP types) were utilized to print the retainers of the 4 experimental groups. See Table 1 for technical specifications. The control group's retainers were fabricated using the PFTT.

3D-Printers

The Form3B printer (Formlabs, Somerville, MA, USA) utilizes an SLA printing technology and claims to build on "Advanced Low Force Stereolithography" to produce consistent and accurate prints, down to a 25 micron resolution.[9] The NextDent 5100 (3D Systems, Rock Hill, SC, USA) is a DLP printer with "Figure 4™ technology", which generates a thin oxygen inhibition layer. Because of this, objects are printed near-continuously without the need to pause. NextDent 5100 also accepts a broad range of print materials, including the only resin in this study being marketed for use in direct printing retainers.[10,11] The SprintRay Pro S (SprintRay, Los Angeles, CA, USA) DLP printer has a print speed of 2 inches per hour. It offers an open certified materials platform that expands the range of accepted resins beyond the company's proprietary offerings.[12] The Asiga Pro 4K 80 (Asiga, Alexandria, Australia) DLP printer has one of the largest build platforms in its class and has an open material system accepting over 350 different resins for printing.[13]

Master STL File

A physical maxillary cast acquired from a recently completed orthodontic patient served as the template for this study. The undercuts on the physical maxillary cast were blocked out using resin (LC Block-Out Resin, Ultradent, South Jordan, UT, USA). The cast was then optically scanned (R2000, 3Shape, Copenhagen, Denmark) to generate an STL file of the physical maxillary cast. Using that STL file, a master cast was printed in VeroDentPlus (Stratasys, Rehovot, Israel), via an Objet30 (Stratasys, Rehovot, Israel) printer. VeroDentPlus or MED690 is dark beige in color and has an elastic modulus of 2.2 – 3.2 GPa, a flexural strength of 80 – 110 MPa, and a glass transition temperature (Tg) of 52 – 54°C.[14] This master cast served as our "live" patient and, to simulate the clinical workflow, was optically scanned (R2000, 3Shape) to generate a master STL file.

Retainers Made from PFTT

To make the control group retainers, the master STL file was exported to the Objet30 printer, from which seven solid – not hollow – working casts, were printed using VeroDentPlus (Stratasys). The casts were individually placed on the platform of the pressure-based molding machine (Biostar VII, Scheu-Dental, Iserlohn, Germany) at the ideal path of insertion. A sheet of clear polypropylene/ethylene copolymer (ACE Essix with thickness = 0.88mm and ∅ = 125 mm, Dentsply Sirona, Sarasota, FL, USA) was heated and pressed over each cast. Following the manufacturer's instructions, the temperature, heating and cooling times, and pressure were: 220 C, 30 s, 120 s, and 87 psi, respectively. Lastly, the retainers were sectioned and removed from the working cast and polished.

Retainers Made from 3D-Printers

To fabricate the direct 3D-printed retainers, a retainer appliance was designed on the master STL file utilizing 3Shape's Appliance Designer 2019 software (version 1.8.1.1, 3Shape, Copenhagen, Denmark) with a specified thickness of 0.75 mm and a 0 mm offset.[4] The STL file of the appliance was then imported into each of the four printers' proprietary 3D printing software and oriented on the build platforms with added supports based on manufacturer specifications. Seven total retainers were printed by each printer using the previously identified proprietary resins. Following printing, the retainers were washed, dried, and cured following all manufacturer's instructions for post-processing. The printing supports were then removed from each retainer and polished.

Data Analyses

A polyvinyl siloxane impression using Aquasil Ultra + Low Viscosity (Dentsply, Milford, DE, USA) of each retainer's intaglio surface was taken and then digitized via optical scanning (R2000, 3Shape). The STL file per retainer and the master STL file were imported into the metrology software, Geomagic Control X (version 2022.1.0, 3D Systems, Rockhill, SC, USA) and Geomagic Freeform Plus (version 2021.1.25, 3D Systems, Rockhill, SC, USA) platforms. Within Geomagic Freeform Plus (3D Systems), identical planar cuts of each retainer STL file and master STL file were accomplished to isolate a standardized amount of the maxillary arch for analysis. Next, within Geomagic Control X (3D Systems), a best fit algorithm was used to individually marry the intaglio surface for each retainer (test object) to the master STL file (reference object) providing a representation of how accurately the intaglio surface of the retainer reproduced the surface contours of the master cast. A heat map, which depicted the discrepancy between the surface of the master STL file and the intaglio of each retainer, was generated. An average and standard deviation per group was calculated for the following parameters: range of the maximum surface deviation, average surface deviation, and root mean square (RMS) deviation between the retainer and the master cast.

Definitions of measured variables:

- Maximum and minimum points of surface deviation: the largest distance gap between the intaglio surface of the retainer above and below (respectively) the reference surface (master STL file) when they are interposed on each other.

- Range of maximum surface deviation: the absolute difference between the maximum and minimum points of surface deviation.

- Average surface deviation: the average distance of the intaglio surface of the retainer from the reference surface (the master STL file).

- RMS of surface deviation: the average magnitude of the surface-to-surface discrepancy between the intaglio surface of the retainer and the reference cast.

Statistical Analysis

The effect size was estimated from previous studies.[15,16] The required number of samples per group that was needed to satisfy a one-way ANOVA with a type I error of 0.05 and a power of 80% was 6. This study had seven samples per group for any unwarranted tolerance. Data were analyzed with a one-way ANOVA, Tukey's post hoc tests and t-test (α =0.05) using statistical software (JMP version 15.2.0, SAS Institute Inc., Cary, NC, USA).

RESULTS

Quantitative Results

There were significant differences in accuracy amongst the groups tested. The measured values of maximum, minimum, range of maximum surface deviation, average surface deviation, and RMS between the retainer and master cast for the groups tested are summarized in Table 2.

The range of maximum deviation between the intaglio surfaces of the retainers and master cast showed statistically significant differences amongst groups. See Figure 2. On average, the Form3B group had a significantly smaller range of maximal deviation (0.58 ± 0.074 mm) than all other groups ($p < 0.0254$). This was followed by the Essix group (0.87 ± 0.07 mm). However, the Asiga (1.24 ± 0.24 mm), NextDent (1.47 ± 0.11 mm), and SprintRay (1.23 ± 0.21 mm) groups had significantly larger ranges of maximal deviation than the Form3B and Essix groups ($p < 0.0030$) but were not significantly different from each other ($p > 0.0895$).

On average, the surface deviation between the intaglio surfaces of the retainers and the master cast also showed statistically significant differences amongst the groups. See Figure 3. The Asiga group displayed a significantly higher average surface deviation (0.041 ± 0.008 mm) than all other groups ($p < 0.0001$). This was followed by the NextDent group (0.012 ± 0.013 mm). However, the Form3B (-0.019 ± 0.006 mm) Essix (-0.031 ± 0.003 mm), and SprintRay (-0.033 ± 0.013 mm) groups had a significantly lower average surface deviation than the Asiga and NextDent groups ($p < 0.0001$) but were not significantly different from each other ($p > 0.0775$). Here a negative average surface deviation indicates that the retainers are smaller than the master cast, which can result in a more retentive fit than those retainers that have a positive surface deviation.

The RMS of deviation between the intaglio surface of each retainer group and the master cast showed a progressive scale of significant differences amongst groups. The Form3B had a significantly smaller RMS of surface deviation (0.08 ± 0.01 mm) than all groups ($p < 0.0223$), except the Essix group, which was statistically similar ($p > 0.8922$). The Essix group's RMS (0.10 ± 0.01 mm) was statistically similar to SprintRay (0.15 ± 0.05 mm; $p > 0.2038$) but was significantly smaller than the NextDent (0.18 ± 0.05 mm) and Asiga groups (0.24 ± 0.05 mm; $p < 0.0074$). The RMS for the SprintRay and NextDent groups were similar ($p > 0.5415$), but each was significantly less in RMS of surface deviation than the Asiga group ($p < 0.0382$).

Significant differences in accuracy existed between the additive technique of the 3D-printed retainers tested. The measured values are summarized in Table III. The SLA printed retainers had a significantly smaller range of maximum surface deviation (0.58 ± 0.07 mm) than the DLP printed retainers (1.21 ± 0.28 mm; $|p| < 0.0001$). The SLA printed retainers also had a significantly smaller RMS of surface deviation (0.08 ± 0.01 mm) than the DLP printed retainers

(0.17 ± 0.06 mm; |p| < 0.0001). The average surface deviation of the SLA printed retainers (-0.019 ± 0.006 mm) was significantly lower than the DLP printed retainers (-0.003 ± 0.033 mm; |p| = 0.0172).

Qualitative Results

Heatmap plots with pseudo-color were generated per retainer by assigning a color to each 0.1 mm increase in surface deviation between the overlayed intaglio surface of the retainer and the master cast. The yellow to red color range indicated the intaglio surface of the retainer was above the surface of the master cast, whereas the cyan to dark blue color range indicated the retainer was below the surface of the master cast. Additionally, the green color assigned in Figure 10 represented areas that fell within a 0.125 mm surface deviation tolerance above and below the master cast for the least and most accurate retainer samples.

A consistent pattern and location of inaccuracy associated with the cross-arch dimension and incisor position within each retainer group was readily apparent. See Figures 5, 6, 7, 8, and 9 for representative heatmap plots of Asiga, NextDent, Essix, Form3B, and SprintRay groups respectively.

The cross-arch dimensions of the Asiga and NextDent retainers were consistently wider than the master cast, whereas the cross-arch dimensions for the Essix, Form3B, and SprintRay retainers were consistently narrower than the master cast.

The incisor position of the retainers was also a source of variability. The incisors for the Essix, Form3B, and NextDent retainers were repeatedly located lingual to the master cast, whereas the incisors of the Asiga retainers were positioned more labially. Conversely, the incisor positions for the SprintRay retainers were well centered; however, they demonstrated a deficient labiolingual width in comparison to the master cast.

DISCUSSION

The null hypothesis was rejected: there were significant differences in the accuracy of retainers fabricated via additive manufacturing (experimental groups) compared to retainers fabricated via the PFTT (control). The various measurements generated for the fit of each retainer group provide a different perspective on the overall accuracy. The range of maximum surface deviation for the retainer intaglio surface above and below the master cast showed how aberrant the retainers were at their most inaccurate points. Nonetheless, it did not provide any indication as to whether the maximal deviation was a localized phenomenon in an overall highly accurate retainer, or if the intaglio surface of the retainer did not accurately reproduce the shape of the master cast in general. On the contrary, the RMS of surface deviation between the retainer intaglio and master cast surfaces provided the best measure of the overall accuracy of the retainer groups. This is because the RMS of surface deviation depicted the relationship of the averaged distance between the entire surfaces of the retainer intaglio and master cast. Yet, the RMS did not reveal if there were any localized portions of a retainer that were highly inaccurate in the way the range of maximum surface deviation did. The average surface deviation between the intaglio surface of the retainer and the master cast indicated if the retainer on average fell below (negative values) or above (positive values) the master cast but did not demonstrate how accurately the retainer intaglio recreated the surface of the master cast because the aberrant areas of the retainer above and below the surface of the master cast could average themselves out to give an inappropriate indication that the two surfaces were closely related.

Taken in aggregate, the different measurements painted a complete picture of how well each printer replicated the surface of the master cast. The intaglio surfaces of the retainers from the Asiga, NextDent, and SprintRay printers had relatively small areas that closely replicated the surface of the master cast as indicated by the higher RMS and range of surface deviation measurements. However, the average surface deviation demonstrated that the Asiga retainers had a broad distribution of their surface sitting above the master cast, the Next Dent retainers had an average close to 0mm indicating an even distribution of the intaglio surfaces that sat above and below the master cast, and the intaglio surface of the SprintRay retainers were more often below the surface of the master cast. Conversely, the small RMS and range of surface deviation measurements for the retainers from both the Essix and Form3B groups revealed that a much higher percentage of their intaglio surfaces closely replicated the master cast and the negative average of their surface deviation demonstrated that the intaglio surfaces of the retainers from those groups more often were below the master cast. These results agreed with Jindal et al. (2019)[17], who demonstrated that 3D-printed aligners using the Form2 (Formlabs) were more accurate than thermoformed aligners. Also, Naeem et al. (2022)[18] found that SLA printers were more accurate than DLP printers.

Measurements from this study indicated that Form3B was the most accurate printer and generated retainers similar to a traditional Essix. However, the varying material properties of the resins used in each printer could also have affected the accuracy of the retainers. For example, the Dental LT Clear V2 resin is more rigid than the OrthoFlex and Nightguard Flex resins used in the Asiga, NextDent, and SprintRay printers respectively. The increased flexibility of the resins used in the Asiga, NextDent, and SprintRay printers potentially increased inaccuracy. These errors could also have been amplified by the retainers being printed at a thickness below the manufacturer recommendations which was done in this study to mimic the thickness of traditional Essix retainers. Based on these limitations, the authors suspect that if the retainers from the Asiga, NextDent, and SprintRay groups were reprinted in rigid resin, the statistically significant differences found between experimental groups in this study could potentially be eliminated.

Modifying the design of the print support lattice for the 3D-printed retainers could have also improved the accuracy of the experimental groups. A previous study by Camardella et al. (2017) demonstrated that adding a support bar connecting the posterior region of horseshoe shaped 3D-printed casts significantly improved the transverse accuracy of the printed casts when compared to horseshoe shaped casts without this additional reinforcement.[19] Given that the cross-arch dimension of the printed retainers was the location of the greatest inaccuracy, adding a support bar across the intermolar region of the retainers could have increased the overall accuracy of this fabrication technique.[20]

Despite the statistically significant differences between the experimental and control groups, the accuracy of the retainers from each printer fell within a clinically acceptable range for orthodontic purposes. The highest RMS of surface deviation for any of the printer groups was 0.24 ± 0.05 mm indicating that even the most inaccurate retainers were generally within 0.25 mm of the master cast which is unlikely to cause any adverse effect orthodontically. The findings agreed with Naeem et al. (2022)[18], who also found that SLA and DLP printers generated retainers within a 0.25 mm range of clinical acceptability. The qualitative findings potentially indicate that there is a tendency for the retainer groups to slightly expand (Asiga and NextDent) or constrict (Form3B, Essix, and SprintRay) the posterior transverse arch dimensions. However, the maximum points of deviation for each retainer above and below the master cast are coupled with other highly accurate areas on each tooth, likely resulting in an overall net zero force to move a tooth away from the desired position, which further decreases the clinical significance of the inaccuracy seen within the retainers. Findings from this study, along with results from previously mentioned studies, indicate that the accuracy of current 3D-printing technology is sufficient to direct print orthodontic retainers.[4,17,18]

CONCLUSION

Significant differences in accuracy were found among retainers fabricated from various 3D-printing technologies and the traditional pressure-form thermoplastic technique. Despite these differences, all fabrication methods produced accuracies that were within the clinically acceptable range of 0.25 mm.

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AUTHOR CREDIT STATMENT

Michael Cvelich contributed to conceptualization, methodology, software, investigation, resources, data curation, original draft preparation, visualization, project administration and funding acquisition; William Anderson contributed to conceptualization, methodology and supervision; Christopher Raimondi contributed to conceptualization, methodology, manuscript review and editing, and supervision; Wen Lien contributed to conceptualization, methodology, formal analysis, manuscript review and editing, supervision and funding acquisition.

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Tables/Figures

Table I. Features of 3D printer experimental groups.

Printer	Manufacturer	Additive Technique	Light Source	Wavelength (nm)	Build Platform (cm)	Print Speed	Print Layer Thickness (microns)	Washing Chemical	Resin Used	Flexural Strength (MPa)	Flexural Modulus (MPa)
Form3B [9]	Formlabs	SLA	250mW laser	405	14.5 x 14.5 x 18.5	Variable	25-300	99% Isopropyl Alcohol	Dental LT Clear V2	84	2300
SprintRay Pro 95S [12]	SprintRay	DLP	LED Projector	405	18.2 x 10.2 x 20	2”/hr at 100 microns	50-170	> 91% Isopropyl Alcohol	Nightguard Flex	118	1306
NextDent 5100 [10,11]	3D Systems	DLP	LED Projector	405	12.5 x 7 x 19.6	Up to 14 cm/hr	25-200	> 90% ethanol	Ortho Flex	67	1721
Asiga Pro 4K80 [13]	Asiga	DLP	LED Projector	385 or 405	21.7 x 12.2 x 20	Variable	User defined	Resin specific	Ortho Flex (NextDent)	67	1721

Table II. Surface deviation measurements (mm) averaged within each experimental group.

	Minimum	Maximum	Range (SD)			Average (SD)			RMS (SD)		
Asiga	-0.55	0.69	1.24	(0.24)	**A**	0.041	(0.008)	**A**	0.24	(0.05)	**A**
NextDent	-0.57	0.90	1.47	(0.11)	**A**	0.012	(0.013)	**B**	0.18	(0.05)	**B**
SprintRay	-0.82	0.41	1.23	(0.21)	**A**	-0.033	(0.013)	**C**	0.15	(0.05)	**B, C**
Form3B	-0.35	0.24	0.58	(0.07)	**C**	-0.019	(0.006)	**C**	0.08	(0.01)	**D**
Essix	-0.57	0.31	0.87	(0.07)	**D**	-0.031	(0.003)	**C**	0.10	(0.01)	**C, D**

(**Bolded** letters indicate statistically significant differences).

Table III. Comparison of surface deviation measurements (mm) by printer additive technique.

<table>
<tr><th>Additive Technique</th><th>Average Surface Deviation</th><th>SD</th><th>t-Test p value</th><th>Range of Maximum Surface Deviation</th><th>SD</th><th>t-Test p value</th><th>Root Mean Square</th><th>SD</th><th>t-Test p value</th></tr>
<tr><td>DLP</td><td>-0.003</td><td>0.033</td><td rowspan="2">|p| = 0.0172</td><td>1.21</td><td>0.28</td><td rowspan="2">|p| < 0.0001</td><td>0.17</td><td>0.06</td><td rowspan="2">|p| < 0.0001</td></tr>
<tr><td>SLA</td><td>-0.019</td><td>0.006</td><td>0.58</td><td>0.07</td><td>0.08</td><td>0.01</td></tr>
</table>

Fig 1. Experimental Workflow

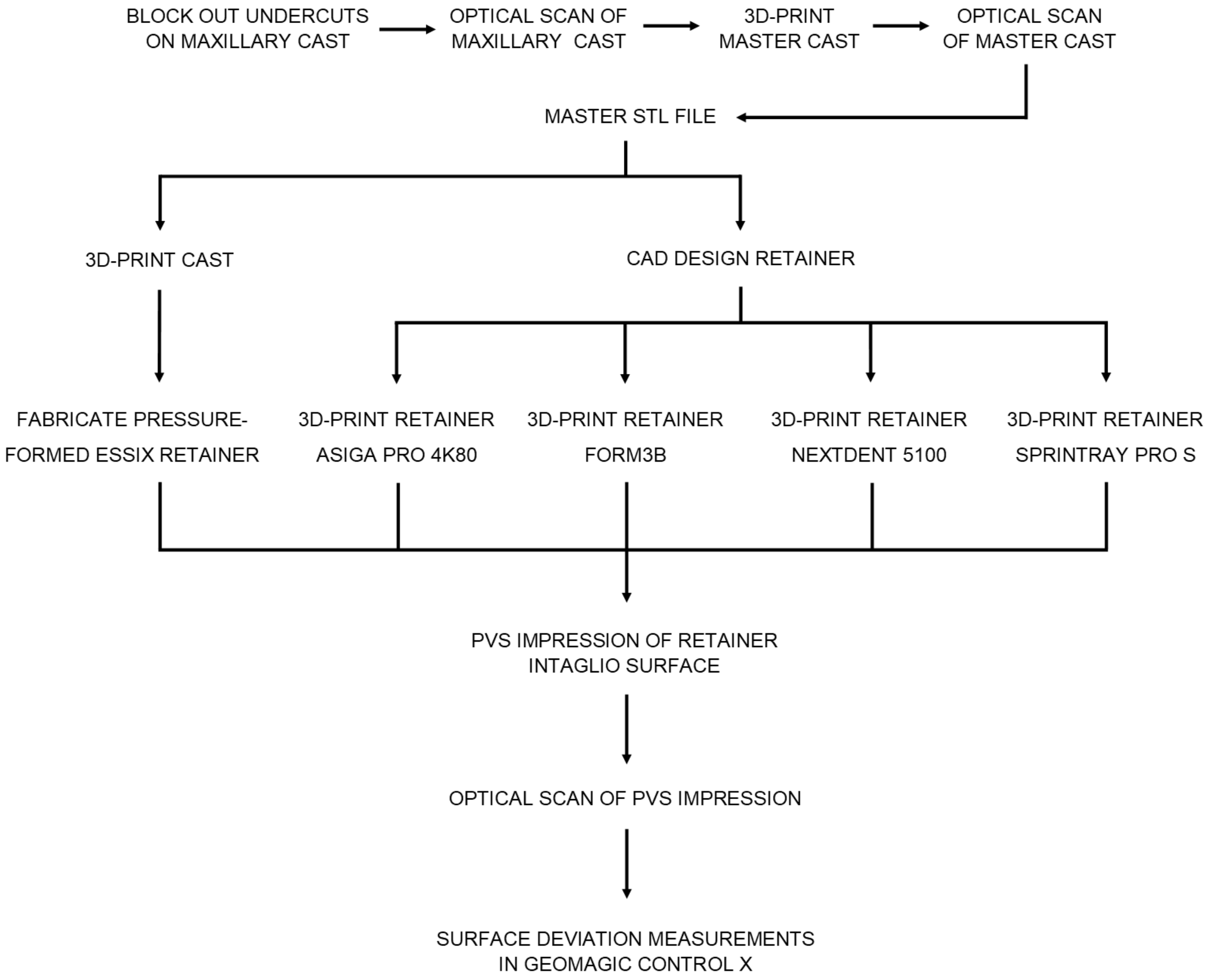

Fig 2. The average range of maximum surface deviation (mm) between the retainer and master cast for each experimental group.

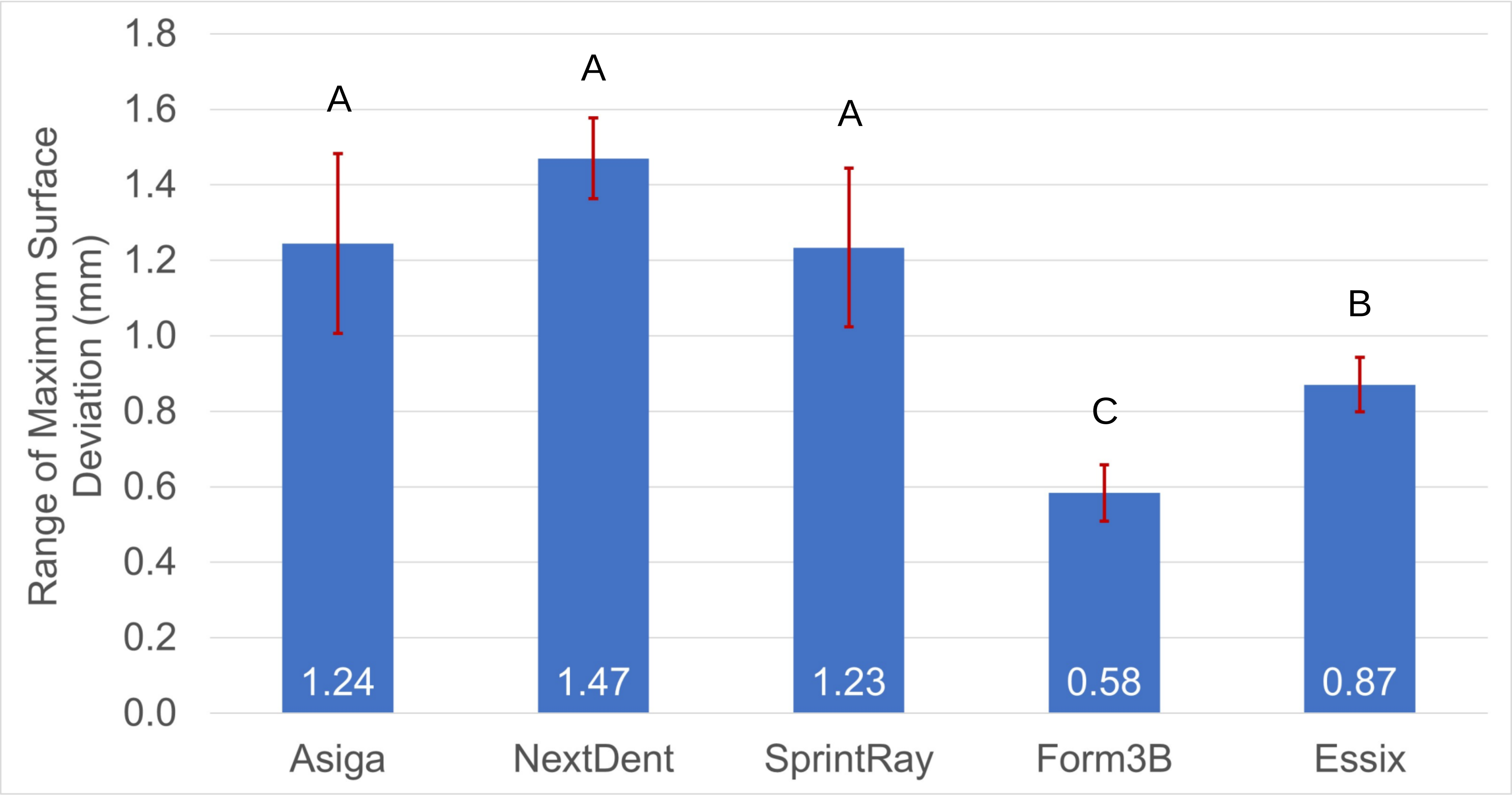

Fig 3. The average surface deviation (mm) between the retainer and the master cast for each experimental group.

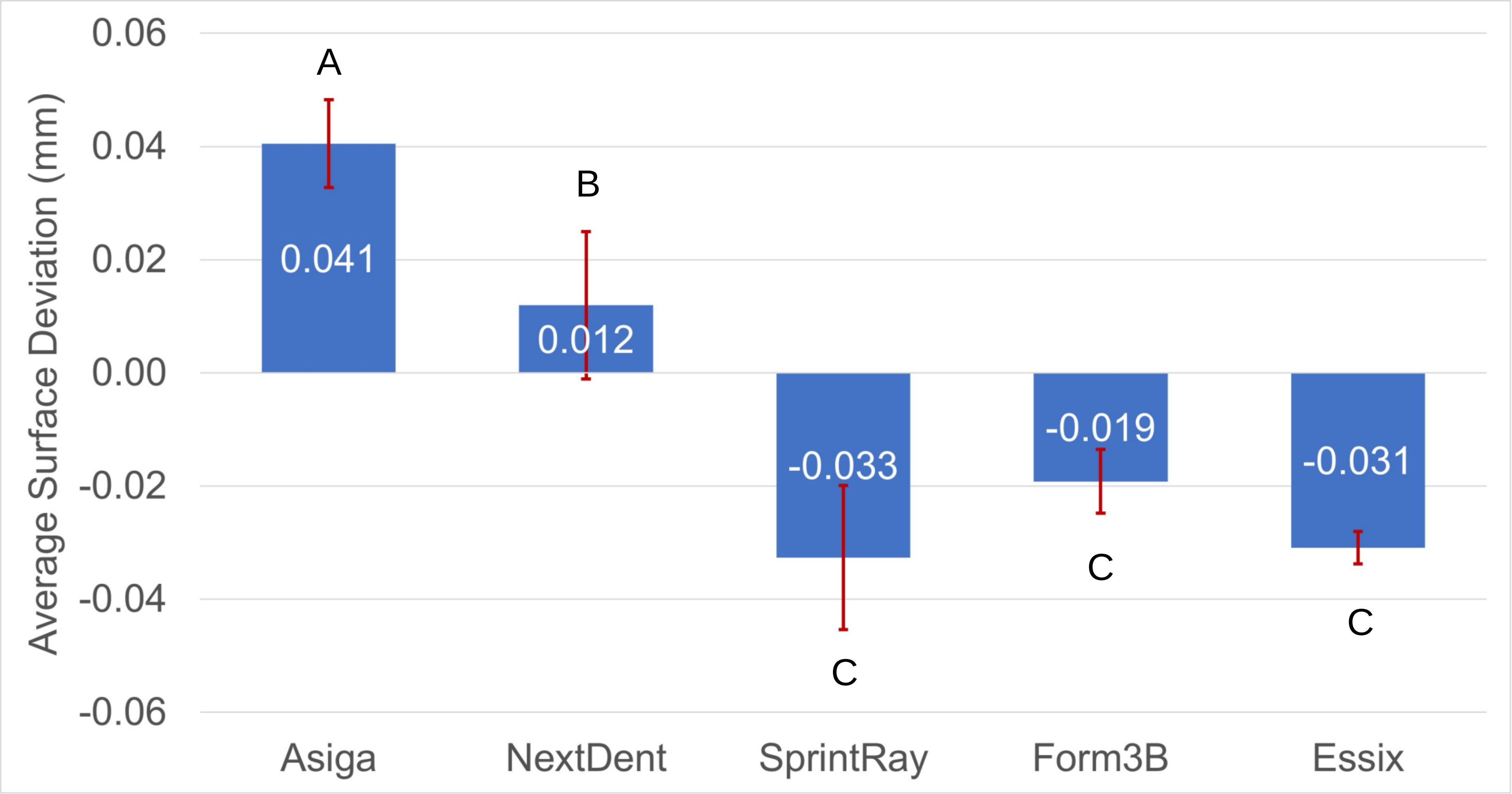

Fig 4. The average Root Mean Square (RMS) of surface deviation (mm) between the retainer and master cast per experimental group.

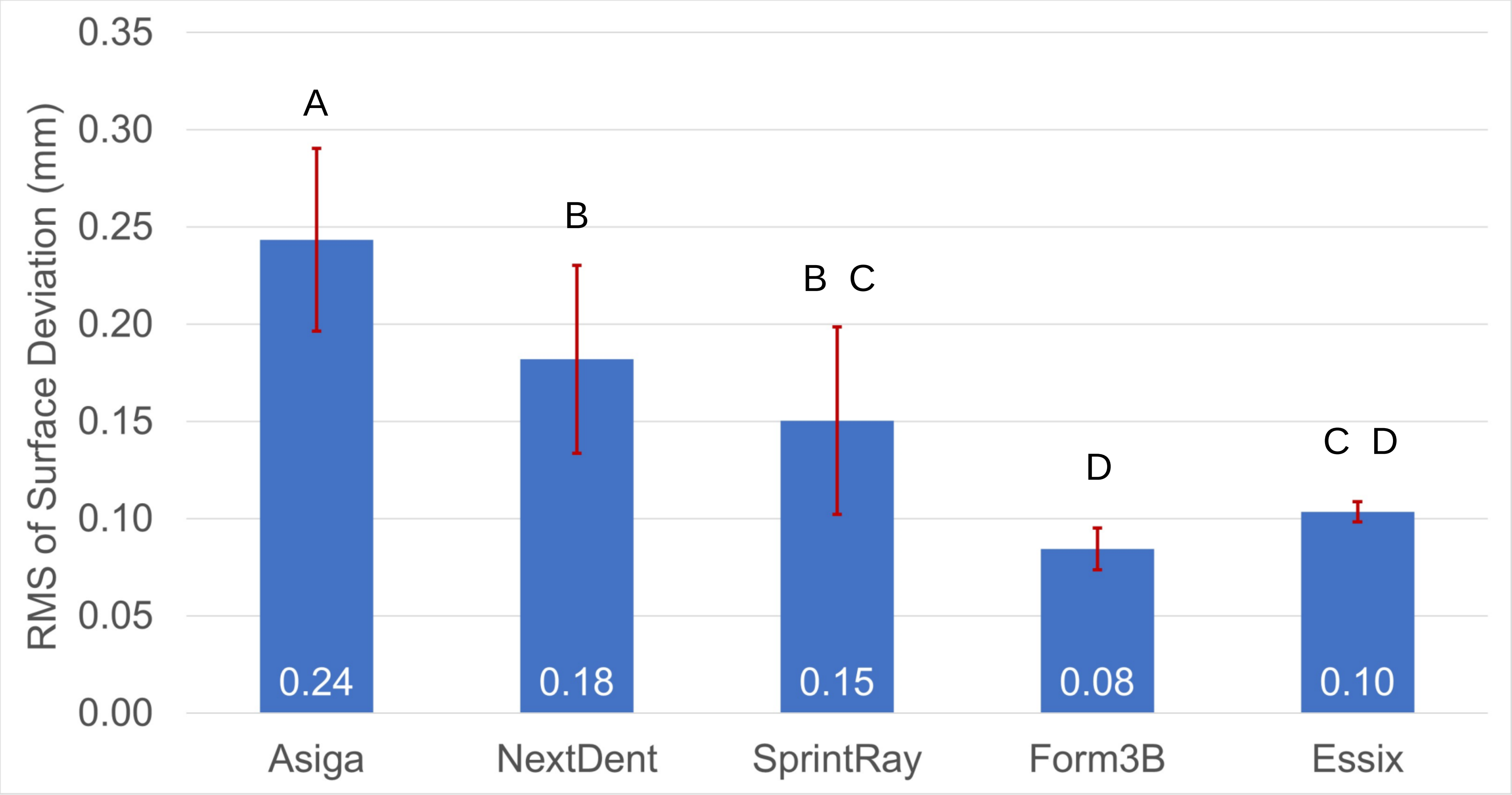

Fig 5. The heatmap and histogram for an Asiga retainer sample showing the location and distribution of surface deviation between the retainer and master cast.

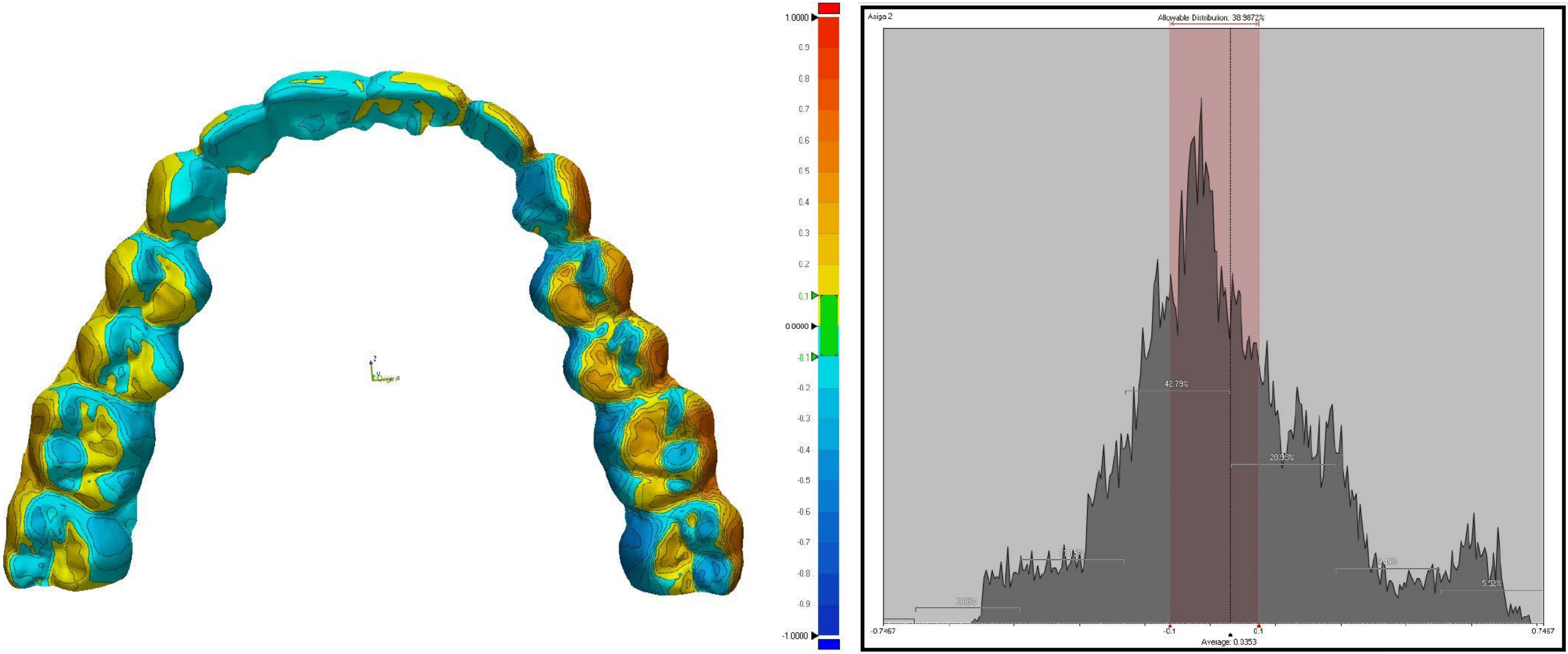

Fig 6. The heatmap and histogram for a NextDent retainer sample showing the location and distribution of surface deviation between the retainer and master cast.

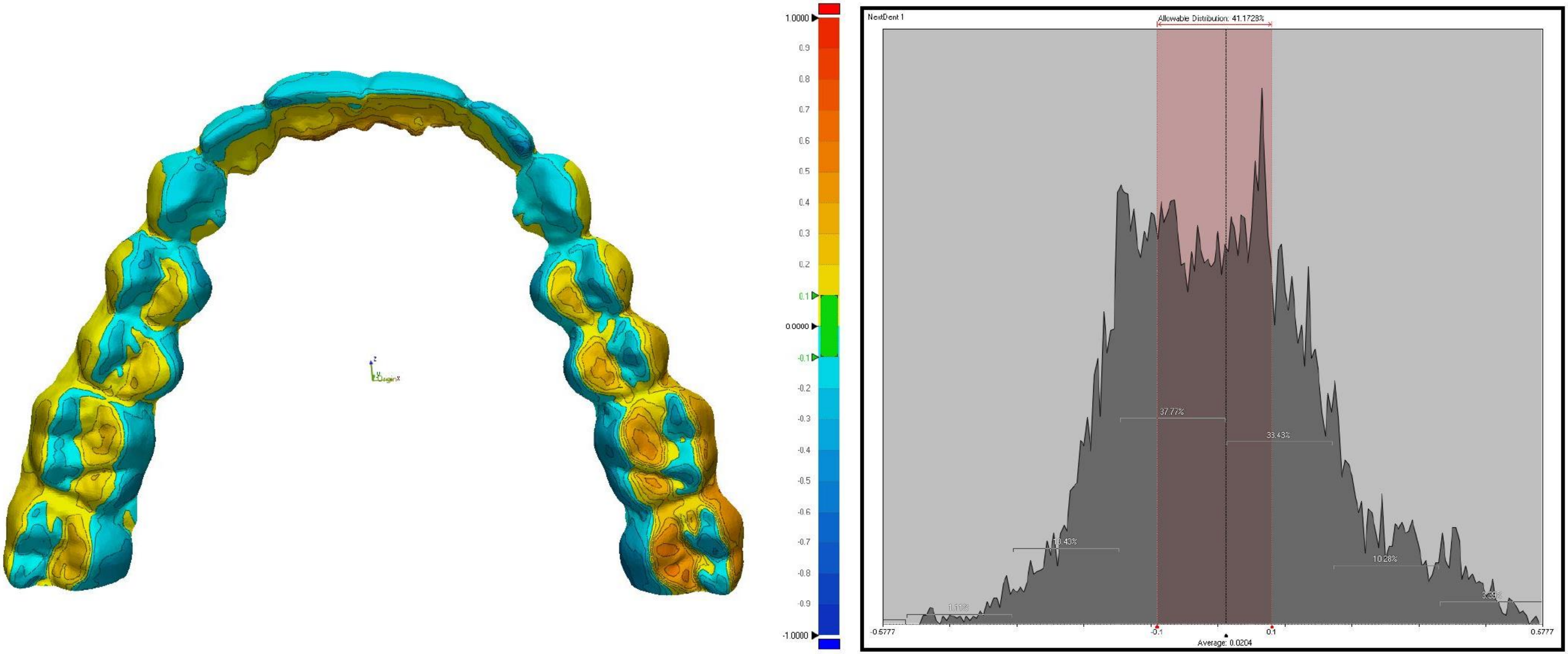

Fig 7. The heatmap and histogram for an Essix retainer sample showing the location and distribution of surface deviation between the retainer and master cast.

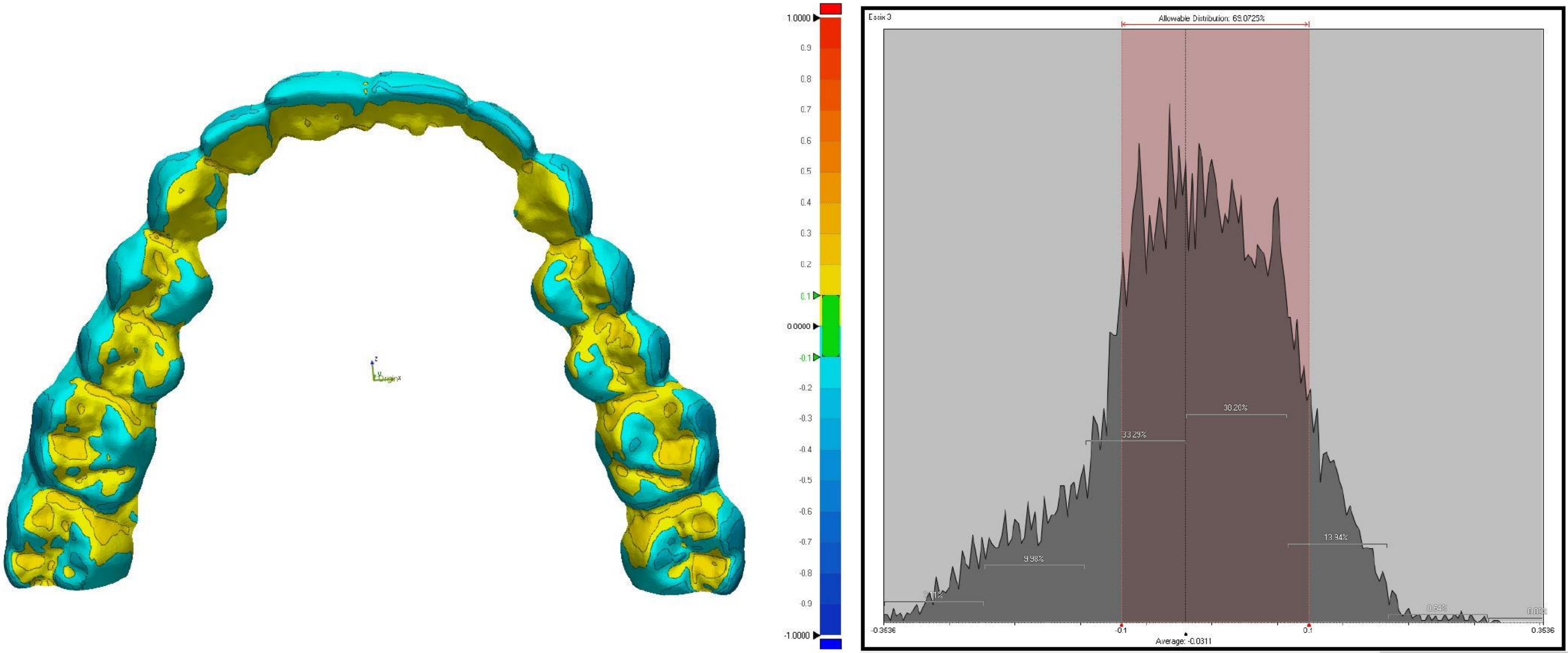

Fig 8. The heatmap and histogram for a Form3B retainer sample showing the location and distribution of surface deviation between the retainer and master cast.

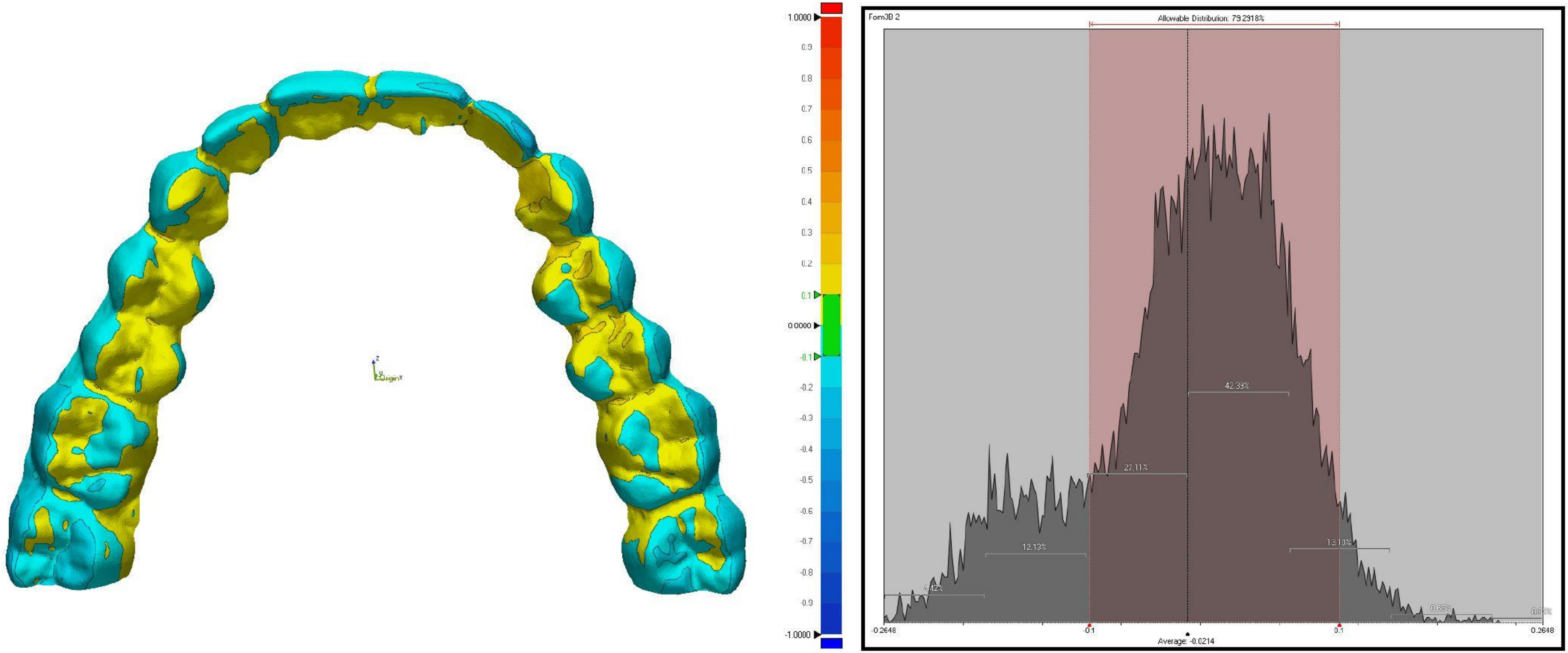

Fig 9. The heatmap and histogram for a SprintRay retainer sample showing the location and distribution of surface deviation between the retainer and master cast.

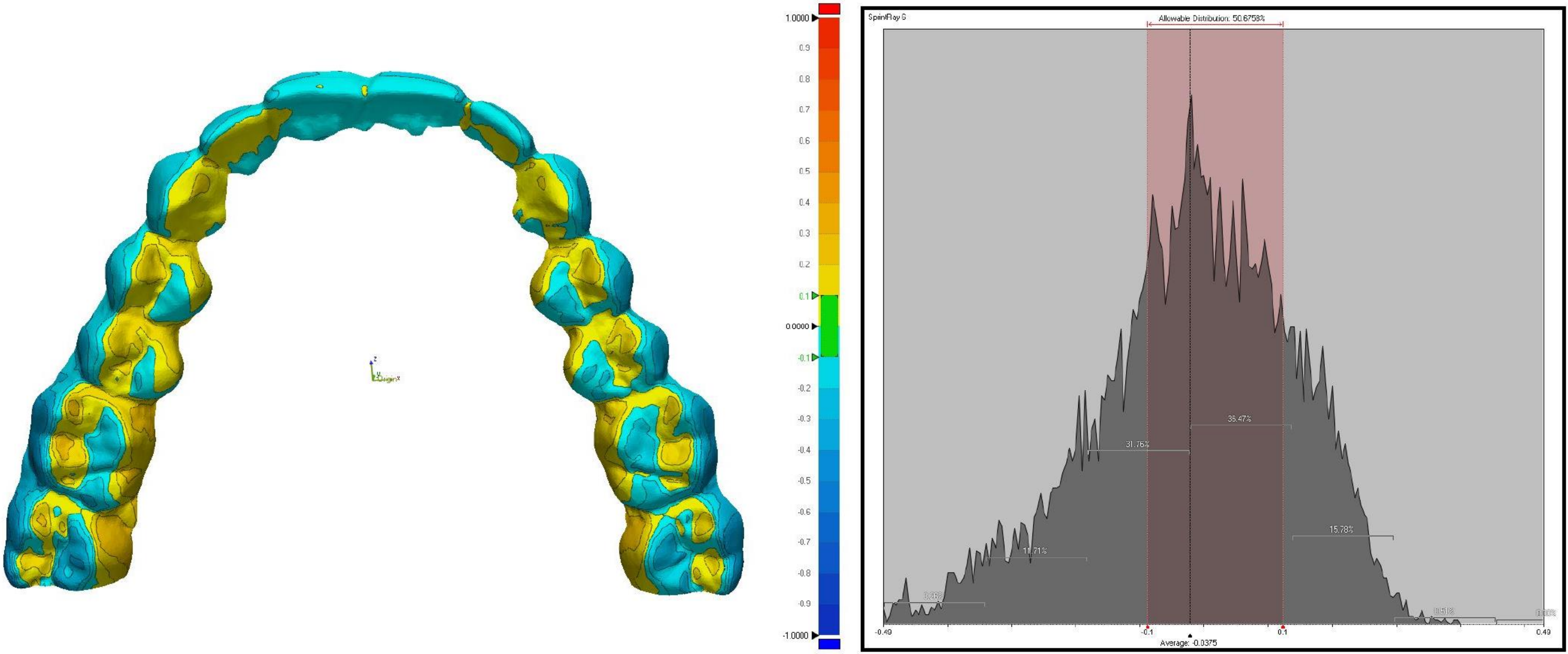

Fig 10. The heatmaps of the least (a.) and most (b.) accurate retainer groups demonstrating intaglio surface areas that fell within a 0.125 mm surface deviation tolerance of the master cast.