Comparison of virtual and physical dimensions in AM resin dental devices and fit of devices with conventionally produced base plates

Al Mortadi, Noor
Eggbeer, Dominic
Lewis, Jeff
Williams, Robert

Introduction:

Computer Aided Design/ Additive Manufacturing (CAD/AM) in medicine enables complex designs that overcome constraints associated with other forms of manual fabrication, a greater level of repeatable precision and improves communication in medicine (Derand et al., 2012; Eggbeer et al., 2007; Metzger et al., 2007; Truscott et al., 2007). CAD/AM systems have been used successfully in various areas of dentistry (Bibb et al., 2015; Goiato et al., 2011; Sassani & Roberts, 1996; Sun et al., 2009; Williams et al., 2004, 2008; Yanping et al., 2006) and related medical applications where accurate and detailed patient specific geometries are desirable (Bibb et al., 2009; Ciocca et al., 2011; Salmi et al., 2012). AM technology has also been applied in orthodontics to produce occlusal splints (Lauren & McIntyre, 2008), a titanium herbst appliance (Farronato et al., 2011), customised lingual brackets and archwires (Grauer et al., 2012; Wiechmann et al., 2003) and removable appliances without wire or brackets (Invisalign system; Align Technology, Inc., Santa Clara, CA (Joffe, 2003; Melkos, 2005). It has also been applied in the production of myofunctional appliances and sleep apnoea devices where a method of inserting wires into a build was described (Al Mortadi et al., 2012, 2013). CAD/AM is a potentially more attractive method of producing complex dental devices than milling since it is superior with regards to the ability to fabricate complex structures that are difficult or impossible with subtractive (machining) technologies (Nasef et al., 2014). However, CAD/ computer aided manufacturing (CAM) have been used on a wide scale in the production of removable prosthodontics (Kanazawa et al., 2011), and fixed prosthodontics (Van Der Zel et al., 2001).

Despite the increased adoption of AM in medicine and in the field of dentistry, there is little in the literature that evaluates the accuracy of AM-produced appliances. This can be perceived as a barrier to more widespread use, since competing laboratory methods of fabrication are well-established; without clear evidence of technical efficacy, CAD/AM is less likely to be adopted in clinical practice. This study is concerned with such issues and makes comparisons of dimensions and tolerances of the physical AM and laboratory-produced components with the intended CAD. This study illustrates an approach using two types of dental devices where CAD/AM is not yet being used, but has potential for application: Andresen and hinged sleep apnoea devices.

Significance of producing Andresen and hinged sleep apnoea devices:

Andresen appliance:

Andresen device consists of a single block (monobloc) which has a simple wire structure embedded. This allowed the principles of the CAD/AM approach to be applied on a relatively simple, yet relevant geometry. The appliance is an old and had led to the development of another type of appliances called Activators. The activators are commonly used in dental practice to correct the malocclusion. Andesen was chosen in this study because it shows the possibility of insertion a wire in a 3D produced appliance.

Sleep Apnoea Device:

Sleep apnoea devices are used to position the upper and lower teeth in a way that enables a clear airway when the wearer is sleeping. The type of device chosen for this study incorporates multiple components, including hinges, that could be produced more efficiently using CAD/AM by exploiting the ability to reduce component assembly.

Method and Materials:

Andresen and sleep apnoea devices were designed using CAD software (FreeForm Modeling Plus, v14, 3D-systems, USA). The virtual production was explained in details and discussed in a previous study (Al Mortadi et al., 2012).

To enable the required comparison of virtual and physical builds, 'L' shaped reference features were connected to an existing CAD models of Andresen and sleep apnoea devices and the defined virtual dimensions were recorded. The reference features were positioned posteriorly of the base plates of both CAD models to provide parallel flat surfaces for subsequent measurement.

In the CAD environment, the dimensions of these 'L' shaped features were 5 mm vertically and horizontally, and 2 mm thick. The 'L' features were positioned either side of the arch posteriorly (at the back of the mouth), at the same level and parallel to one another. They were separated by a distance of 38 mm in the CAD space (Figures 1 & 2).

In addition to 'L' reference features, a cube of dimensions 5 x 5 x 5 mm was positioned on both appliances on the anterior (front) area of the devices (Figure 3). All of the features are shown in Figures 1 and 2 (Figures 1 & 2).

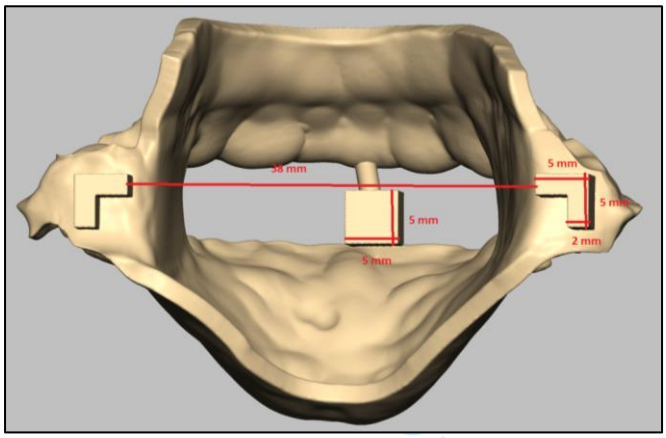

Figure 1: 'L shapes' separated by a 38 mm distance combined into the Andresen device.

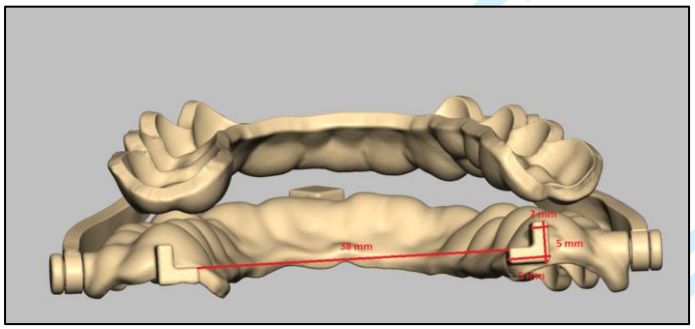

Figure 2: 'L shapes' separated by a distance of 38 mm combined into the sleep apnoea device.

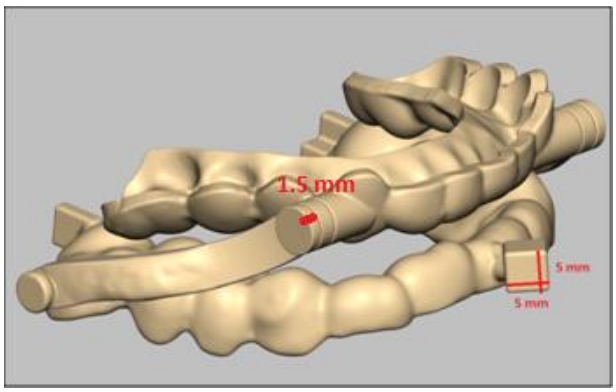

Figure 3: Cube in the anterior region of the sleep apnoea device

The devices including the reference features were fabricated using an AM technique that allowed the hinge components of the sleep apnoea device to be fabricated as a single component, with a resolution suitable for dental device production and in a material analogous to the acrylic polymer used in lab production methods ProJet 3000HD Plus (3D-System). The material was VisiJet EX200 (3D-Systems) and a wax-based support structure that could be removed using low temperature melting in the post-processing stages. XHD mode was used. This has a print resolution of 750 x 750 x 1600 DPI (xyz); 16µ layers.

Vertical, horizontal and sagittal dimensions of the physical cubes were checked ten times with digital callipers and measurements were recorded. The average value of these measurements for each plane was compared to those defined in the CAD environment.

***In vitro* assessment of the accuracy of fit of CAD/AM and conventionally produced appliances:**

The fit of AM machine-produced (VisiJet EX200, 3D-Systems ProJet 3000HD Plus) base plates and conventional base plates produced using lab production methods by a qualified dental technician from Orthoresin (an auto-polymerising, acrylic-based resin, Dentsply, Surrey, UK) were compared. Three upper and three lower base plates produced using each method were compared. Each plate was designed and fabricated using the same dental cast (a replica of the oral cavity) to eliminate the potential for inaccuracy associated with the production of multiple casts. The conventional plates covered the teeth on the buccal and lingual surfaces as well as extended 1 - 2 mm below the gingival lines. From the posterior area, the plates extended 2 mm behind the second molars.

The fitting surfaces were examined and inspected for any space which may exist between the fitting surfaces and the dental casts by using silicone impression materials as a disclosing media which filled in any gaps, was allowed to set, and could then be measured to determine the space. Affinis, light body, (Coltène Whaledent, Ohio 44223, USA) was used. Such materials have been used previously as disclosing media and for a similar purpose as this study (Troendle et al., 1991). The method resulted in 30 readings for AM-produced baseplates and 30 for orthoresin baseplates, which enabled the determination of statistically significant differences. Five measurements of the disclosing medium were

taken for each plate constructed in either material, i.e. five points for the mandibular plate and five for the maxillary plate (Figures 4 & 5).

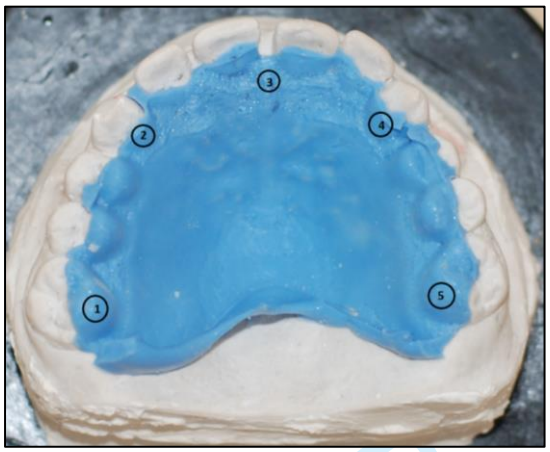

Figure 4: The points used for measurement shown on the upper cast

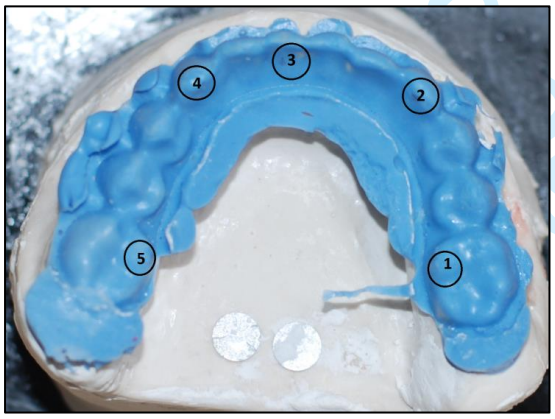

Figure 5: The points used for measurement shown on the lower cast

The fit of the plates was measured when certain areas of specific teeth of the silicone disclosing medium were measured for thickness (Figure 5). These areas were the cusp tips of the premolars and molars, mid of central incisors ''incisive papilla'', and the cingulum on the left lower central incisor as these provided locatable points for comparison. These points were chosen because they formed a reasonably evenly distributed area and provided landmarks; which meant the same point could be located and measurements taken on different baseplates. Furthermore, these points could normally be expected to have a good contact between the devices.

The target thickness of the plates was 2 mm over the areas measured. In practice there was a small variation around this target, + or – 0.03mm for digitally produced and conventionally produced plates.

The thickness of the silicone disclosing medium was measured using a measuring device developed for this study (Figure 6). This was made by using 0.5 mm. stainless steel orthodontic wire and its associated tubing with a good fit. The tip of the wire was carefully fashioned to a point. Measurement was accomplished by positioning the disclosing medium 'in situ' on the fitting surface of the plates and inserting the wire in the disclosing media until contact with the hard baseplate material was achieved. Next the tube was carefully slid along the wire until it contacted the disclosing media. The device was then carefully withdrawn and the distance between the tip of the wire and the edge of the tube was taken using a digital calliper (Fino Caliper, DT & Shop, Bad Bocket, Germany, www.dt-wright.co.uk). The calliper used had a resolution of 0.01 mm. and complied with the ISO 9001 standard. This method represented an accessible and practical solution that can be undertaken by dental technologists, but it is acknowledged that alternative, more advanced methods, such as Coordinate Measuring Methods (CMM) could be used.

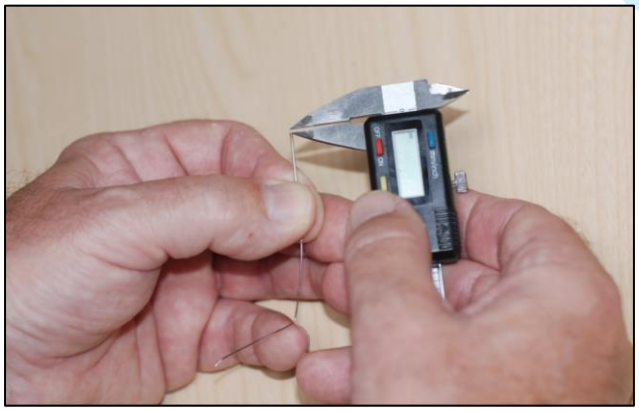

Figure 6: The developed measuring device

Five measurements of the disclosing medium were taken for each plate, five points for the mandibular plate and five for the maxillary plate. The upper was measured at the mesiolingual cusp of right and left 1st molars, lingual cusps of 1st premolars, and the incisive papilla. For the lower, measurements were taken at the mesiolingual cusps of right and left 1st molars, cusp tips of right and left canines, and cingulum of left central incisor.

Results:

Three physical builds of the sleep apnoea device and three builds of the Andresen base are shown in figures 1-3. The 'L' shapes and cube shapes which were connected to CAD models of the devices defined to precise virtual measurements were measured in the physical models.

Ten measurements were taken for each dimension indicated in Figures 7 and 8 for the sleep apnoea device. Similarly, measurements were taken on the Andresen base.

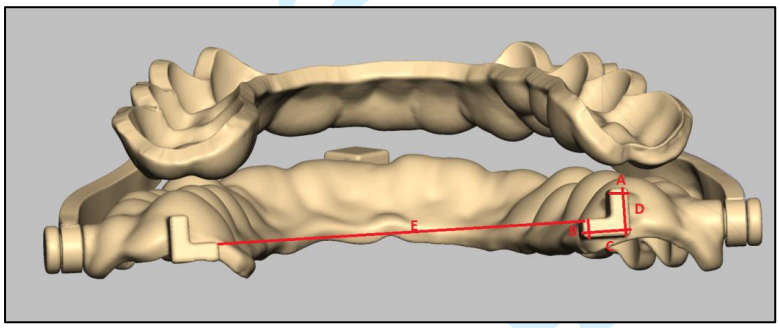

Figure 7: The posterior parts of the sleep apnoea device with the measured dimensions indicated as 'A', 'B','C', 'D' and 'E'

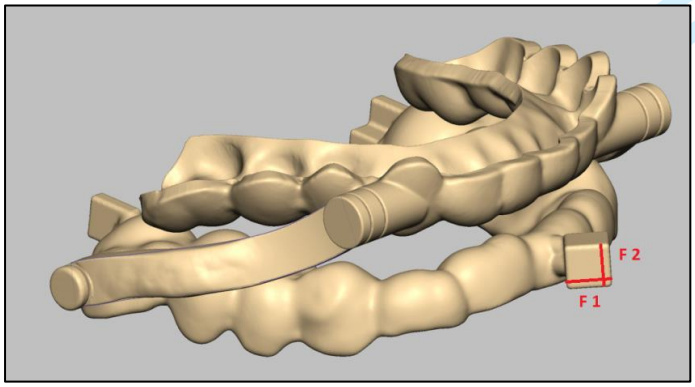

Figure 8: The measured dimensions of the cube positioned anteriorly on the sleep apnoea device ('F1' and 'F2')

The physical dimensions of the 'L' shapes and cubes placed on the three specially-built Andresen bases are listed in Table 1. Ten measurements were taken for each dimension, averaged, and completed on three devices.

Table 1: Physical dimensions of the measurement points of the first, second, and third Andresen device in mm

	First device		Second device		Third device	
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
Right A	2.08	0.044	2.01	0.033	2.03	0.039
Right B	2.03	0.034	1.99	0.041	2.04	0.043
Right C	5.07	0.026	4.97	0.025	5.07	0.018
Right D	4.98	0.023	4.82	0.021	5.00	0.033
Left A	1.99	0.028	2.00	0.027	2.05	0.026
Left B	1.95	0.033	1.94	0.021	2.06	0.034
Left C	4.99	0.047	4.97	0.043	5.02	0.027
Left D	5.04	0.032	4.87	0.049	5.00	0.036
E	38.07	0.111	38.00	0.051	37.86	0.097
F1	5.01	0.031	4.91	0.038	4.99	0.036
F2	5.99	0.040	4.97	0.080	5.01	0.032

The physical dimensions of the 'L' shapes and cubes placed on three physical sleep apnoea devices are listed in Table 2.

Table 2: Physical dimensions of the measurement points of the first, second, and third sleep apnoea device in mm

	First device		Second device		Third device	
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
Right A	2.08	0.036	1.96	0.011	2.07	0.023
Right B	2.00	0.044	1.99	0.029	2.03	0.025
Right C	5.04	0.029	4.93	0.049	5.04	0.037
Right D	4.97	0.029	4.88	0.020	4.97	0.026
Left A	2.04	0.025	2.00	0.039	2.02	0.034
Left B	1.89	0.049	1.88	0.044	1.97	0.054
Left C	1.01	0.048	4.93	0.018	5.02	0.039
Left D	4.10	0.056	4.92	0.016	4.98	0.030
E	38.98	0.032	38.90	0.090	39.22	0.094
F1	4.97	0.041	5.00	0.023	5.00	0.027
F2	5.03	0.059	4.97	0.038	5.03	0.020

Comparison the fitting surfaces of built and conventionally produced baseplates '*in vitro*':

Three upper and three lower base plates produced using a CAD/AM method and three upper and three lower conventional plates produced by the conventional **"sprinkle on" Laboratory** method were measured. For each plate, five measurements of the disclosing medium were taken, i.e. five points for the mandibular plate and five for the maxillary plate (Figures 4 and 5) (See also table 3).

Table 3: represents the areas measured for gap clearance

Upper	Point 1	Right mesiolingual cusp of 1st molar
Upper	Point 2	Right lingual cusp of 1st premolar
Upper	Point 3	Incisal papilla
Upper	Point 4	Left lingual cusp of 1st premolar
Upper	Point 5	Left mesiolingual cusp of 1st molar
Lower	Point 1	Right mesiolingual cusp of 1st molar
Lower	Point 2	Right cusp of canine
Lower	Point 3	Cingulum of left central incisor
Lower	Point 4	Left cusp of canine
Lower	Point 5	Left mesiolingual cusp of 1st molar

Table 4: The average of ten measurements of disclosing media in mm taken at each point of a plate covering a cusp, cingulum or papilla produced by AM and Orthoresin

Base plate number	**The measured point**	**Upper/Lower**	**AM base plates**	**Auto-polymerising acrylic base plates**
Base plate 1	Point 1	Upper	0.374	0.350
	Point 2	Upper	0.267	0.292
	Point 3	Upper	0.324	0.410
	Point 4	Upper	0.464	0.420
	Point 5	Upper	0.685	0.441
Base plate 2	Point 1	Upper	0.306	0.543
	Point 2	Upper	0.415	0.361

	Point 3	Upper	0.752	0.249
	Point 4	Upper	0.460	0.245
	Point 5	Upper	0.768	0.359
Base plate 3	Point 1	Upper	0.550	0.253
	Point 2	Upper	0.368	0.219
	Point 3	Upper	0.308	0.289
	Point 4	Upper	0.514	0.300
	Point 5	Upper	0.883	0.406
Base plate 4	Point 1	Lower	0.302	0.505
	Point 2	Lower	0.356	0.407
	Point 3	Lower	0.289	0.569
	Point 4	Lower	0.522	0.569
	Point 5	Lower	0.340	0.509
Base plate 5	Point 1	Lower	0.474	0.068
	Point 2	Lower	0.868	0.150
	Point 3	Lower	0.551	0.326
	Point 4	Lower	0.678	0.169
	Point 5	Lower	0.561	0.329
Base plate 6	Point 1	Lower	0.451	0.884
	Point 2	Lower	0.275	0.392
	Point 3	Lower	0.280	0.457
	Point 4	Lower	0.377	0.414
	Point 5	Lower	0.299	0.435
			Mean = 0.469	Mean = 0.369
			Variance = 0.033	Variance = 0.023

Statistical analysis was carried out using a t-test in Excel to determine significance. The low p value indicates that the null hypothesis can be rejected, i.e. that there are no statistically significant differences in the results. The variances in the above table are small which indicate that the data tend to be very close to the mean and hence to each other, indicating a good level of reliability.

Results concluded that was no statistical difference in the virtual and physical measurements.

Assessment of the fitting surfaces *in vitro*:

A disclosing (impression) medium was used to detect the presence and size of gaps between the bases and a dental cast. AM-built plates were compared with conventionally lab-fabricated base plates. The mean gap of conventional base plates was less than that of AM-fabricated base plates and hence on average the auto-polymerising base plates were closer to the casts at the measurement points than the AM plates. However, the mean difference between the categories is extremely small, being a tenth of a millimetre. Hence, any noticeable practical difference noticeable in clinical application would be unlikely. No published research regarding what is an acceptable tolerance of fit could be found in relation to this field. Although a gap of 0.884 mm occurs only once in the results of the auto-polymerising base plates to cast, the result suggests that it is possible that such gaps do occur in fitted appliances used routinely in practice. However, poor fit has not been reported as a problem in the literature, and thus it could be surmised that this degree of gap clearance was acceptable.

Discussion:

With acknowledged growth in the application of CAD/AM techniques in medicine and dentistry, the need to ensure devices can be designed and fabricated to clinically-relevant levels is paramount to validate suitability for more widespread use. Combined with the lack of consensus on what represents a clinically-suitable level of accuracy and fit, bespoke, organic and freeform shape geometries, as found in dental appliances, are a challenge when trying to measure these factors. This study presents a method of analysing accuracy and fit of CAD/AM-produced dental devices that could be replicated without the need for specialist engineering equipment. With an increased number of laboratories and companies seeking to employ CAD/AM, the techniques presented could be used to validate in-house production. The results indicate that CAD/AM is capable of meeting clinically-relevant levels of accuracy, but this study utilised an AM process where the materials are not yet approved for long-term intra-oral use. Whilst CAD is a well-proven design

methodology, material properties represent one of the most significant hurdles for intra-oral application of AM processes. Further research is therefore required to analyse the material mechanical and biocompatibility properties or confirm whether alternative AM methods that utilise suitable materials can be used in the production of the dental appliances discussed.

Conclusion:

The results indicate that CAD/AM techniques represent a potentially viable method for designing and producing the two types of dental appliance studied. This was confirmed through accuracy and comparison studies between production methods and subsequent statistical analysis. However, whilst it may be possible to achieve clinically-suitable levels of accuracy, limitations with the material biocompatibility and mechanical properties mean that further work is required to validate CAD/AM as suitable for long-term intra-oral device fabrication.

Acknowledgment:

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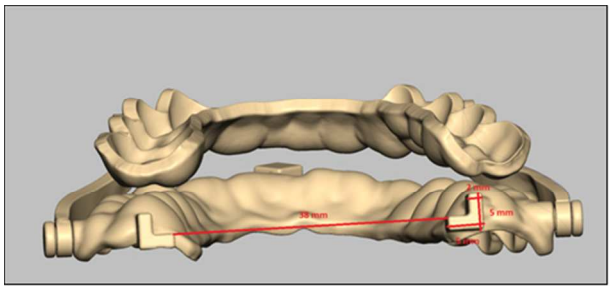

Figure 1: 'L shapes' separated by a 38 mm distance combined into the Andresen device.

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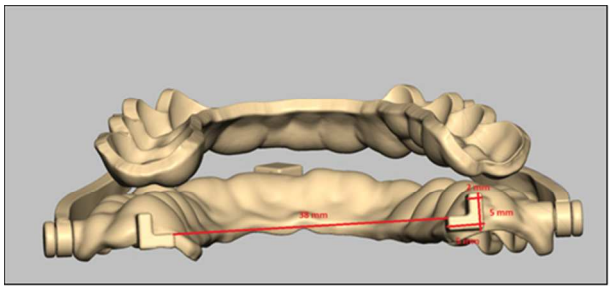

Figure 2: 'L shapes' separated by a distance of 38 mm combined into the sleep apnoea device.

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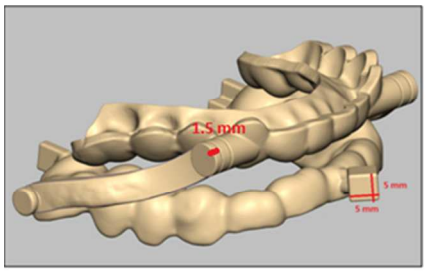

Figure 3: Cube in the anterior region of the sleep apnoea device

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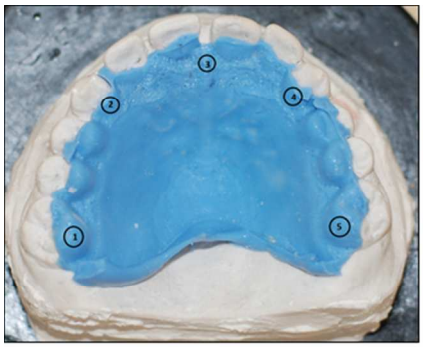

Figure 4: The points used for measurement shown on the upper cast

216x121mm (96 x 96 DPI)

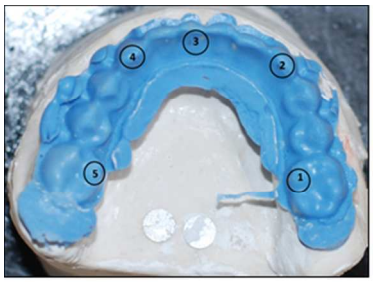

Figure 5: The points used for measurement shown on the lower cast

216x121mm (96 x 96 DPI)

Figure 6: The developed measuring device

216x121mm (96 x 96 DPI)

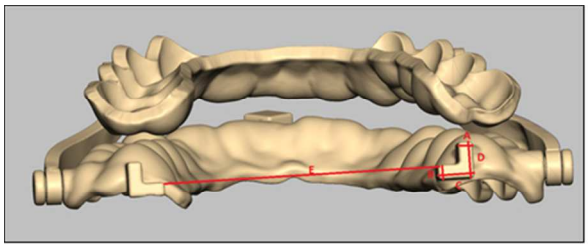

Figure 7: The posterior parts of the sleep apnoea device with the measured dimensions indicated as 'A', 'B','C', 'D' and 'E'

216x121mm (96 x 96 DPI)

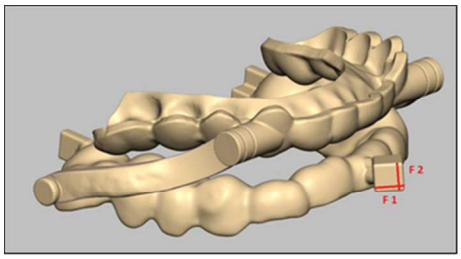

Figure 8: The measured dimensions of the cube positioned anteriorly on the sleep apnoea device ('F1' and 'F2')

216x121mm (96 x 96 DPI)

	First device		Second device		Third device	
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
Right A	2.08	0.044	2.01	0.033	2.03	0.039
Right B	2.03	0.034	1.99	0.041	2.04	0.043
Right C	5.07	0.026	4.97	0.025	5.07	0.018
Right D	4.98	0.023	4.82	0.021	5.00	0.033
Left A	1.99	0.028	2.00	0.027	2.05	0.026
Left B	1.95	0.033	1.94	0.021	2.06	0.034
Left C	4.99	0.047	4.97	0.043	5.02	0.027
Left D	5.04	0.032	4.87	0.049	5.00	0.036
E	38.07	0.111	38.00	0.051	37.86	0.097
F1	5.01	0.031	4.91	0.038	4.99	0.036
F2	5.99	0.040	4.97	0.080	5.01	0.032

	First device		Second device		Third device	
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
Right A	2.08	0.036	1.96	0.011	2.07	0.023
Right B	2.00	0.044	1.99	0.029	2.03	0.025
Right C	5.04	0.029	4.93	0.049	5.04	0.037
Right D	4.97	0.029	4.88	0.020	4.97	0.026
Left A	2.04	0.025	2.00	0.039	2.02	0.034
Left B	1.89	0.049	1.88	0.044	1.97	0.054
Left C	1.01	0.048	4.93	0.018	5.02	0.039
Left D	4.10	0.056	4.92	0.016	4.98	0.030
E	38.98	0.032	38.90	0.090	39.22	0.094
F1	4.97	0.041	5.00	0.023	5.00	0.027
F2	5.03	0.059	4.97	0.038	5.03	0.020

Base plate number	The measured point	Upper/Lower	AM base plates	Auto-polymerising acrylic base plates
Base plate 1	Point 1	Upper	0.374	0.350
	Point 2	Upper	0.267	0.292
	Point 3	Upper	0.324	0.410
	Point 4	Upper	0.464	0.420
	Point 5	Upper	0.685	0.441
Base plate 2	Point 1	Upper	0.306	0.543
	Point 2	Upper	0.415	0.361
	Point 3	Upper	0.752	0.249
	Point 4	Upper	0.460	0.245
	Point 5	Upper	0.768	0.359
Base plate 3	Point 1	Upper	0.550	0.253
	Point 2	Upper	0.368	0.219
	Point 3	Upper	0.308	0.289
	Point 4	Upper	0.514	0.300
	Point 5	Upper	0.883	0.406
Base plate 4	Point 1	Lower	0.302	0.505
	Point 2	Lower	0.356	0.407
	Point 3	Lower	0.289	0.569
	Point 4	Lower	0.522	0.569
	Point 5	Lower	0.340	0.509
Base plate 5	Point 1	Lower	0.474	0.068
	Point 2	Lower	0.868	0.150
	Point 3	Lower	0.551	0.326
	Point 4	Lower	0.678	0.169
	Point 5	Lower	0.561	0.329
Base plate 6	Point 1	Lower	0.451	0.884
	Point 2	Lower	0.275	0.392
	Point 3	Lower	0.280	0.457
	Point 4	Lower	0.377	0.414
	Point 5	Lower	0.299	0.435
			Mean = 0.469	Mean = 0.369
			Variance = 0.033	Variance = 0.023

Upper	Point 1	Right mesiolingual cusp of 1st molar
Upper	Point 2	Right lingual cusp of 1st premolar
Upper	Point 3	Incisal papilla
Upper	Point 4	Left lingual cusp of 1st premolar
Upper	Point 5	Left mesiolingual cusp of 1st molar
Lower	Point 1	Right mesiolingual cusp of 1st molar
Lower	Point 2	Right cusp of canine
Lower	Point 3	Cingulum of left central incisor
Lower	Point 4	Left cusp of canine
Lower	Point 5	Left mesiolingual cusp of 1st molar