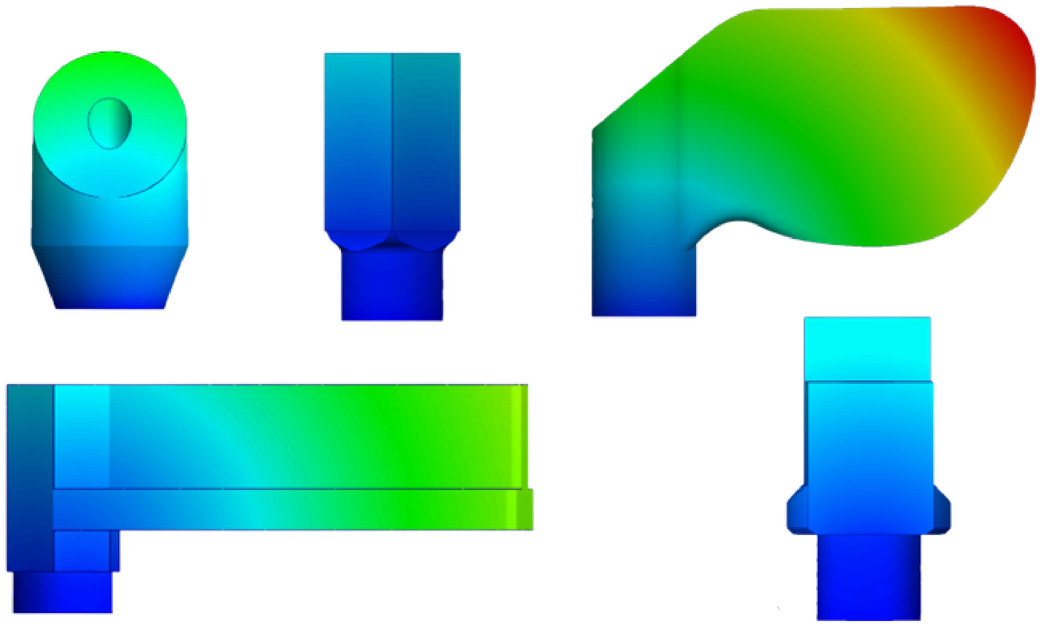
THERMAL EXPANSION OF DENTAL SCANBODIES AT BODY TEMPERATURE: A FINITE ELEMENT ANALYSIS APPROACH

Katie Vinterella[1]

[1]Imetric Research, Huntsville, AL



Abstract

When objects are exposed to a temperature change, they experience a change in size due to the phenomenon of thermal expansion. Because of thermal expansion, temperature and weather changes can have a big impact on the function and stability of objects. Luckily, engineers and architects incorporate safeguards into their designs to allow objects to expand and contract in response to changes in temperature without compromising structural integrity. Without these safeguards, railroad tracks would warp, and bridges would buckle as they expand in the heat of the summer [3]. In implant dentistry, factoring in the effects of thermal expansion is just as important to maintain the accuracy required for a successful full-arch case. Dental scanbodies are frequently exposed to various temperature changes during daily use, such as when they are placed in a patient's mouth during measurement or when they are sterilized in an autoclave.

Finite element analysis (FEA) is a computational method used to simulate an object's behavior under applied conditions. In this study, FEA is used to simulate the thermal expansion of various dental scanbodies when exposed to the environment of the patient's mouth.

Background

The amount of expansion an object undergoes when exposed to heat can be written as a function of time and temperature. Although unconstrained objects will expand three-dimensionally, engineers frequently use the linear approximation of thermal expansion when dealing with solid objects (Eq 1) [2,3].

$$\Delta L = a L \Delta T \qquad \textbf{Eq. 1}$$

Where: ΔL is the change in length, a is the coefficient of linear expansion, and ΔT is the change in temperature.

Based on Eq 1., the amount of expansion an object experiences is proportional to the length of the object. This means dental scanbodies with greater size will undergo greater amounts of expansion when exposed to heat, even at body temperature.

Thermal expansion is also proportional to the coefficient of linear thermal expansion (CTE). This coefficient is an intrinsic material property that can vary based on the temperature [3]. Within a certain range of temperatures, we can assume that any natural variation of the CTE is negligible, although some material data sheets provide CTE values that correspond to different ranges of temperatures [1]. Below is a table of CTE values for materials that are commonly used in dental components:

Titanium Alloy (Ti-6Al-4V)	8.6e-06 (1/K)
Aluminum Alloy	2.36e-05 (1/K)
PEEK – Body Temp	3.78e-05 (1/K)

Table 1-. *Coefficients of linear thermal expansion for materials used in dental scanbodies*

As seen in Table 1, the CTE value for aluminum alloy is 2.7 times larger than Ti-6Al-4V, and the CTE value for polyether ether ketone (PEEK) is 4.4 times larger than Ti-6Al-4V. Because of the higher CTE value, a scanbody that is made of PEEK will experience greater amounts of expansion compared to a scanbody of the same size that is made of aluminum and titanium alloy. Titanium has the smallest CTE value and will, therefore, experience less expansion than PEEK and aluminum alloy components of the same size.

Materials and Methodology

To prepare for analysis, various dental scanbodies were reverse-engineered using SOLIDWORKS 2023, and subsequent finite element analysis was performed using SOLIDWORKS Simulation (Dassault Systèmes). To prepare for simulation, a curvature-based tetrahedral mesh was applied. For static studies, an h-adaptive tetrahedral mesh was used to capture the geometric complexity of the scanbodies. To ensure that the numerical results were independent of the mesh element density, a manual mesh convergence study was performed prior to the final simulation. The final number of total nodes ranged from 13,441 to 14,718, and the number of total elements ranged from 8,304 to 16,902, depending on the size and geometric complexity of the scanbody. Applied materials were linear elastic isotropic and assumed to be homogeneous and defect-free.

Transient thermal studies were conducted to simulate the thermal gradient of the scanbodies after being exposed to body temperature air (37° C). Two different exposure times were computed—one at 90 seconds to simulate the standard time to place scanbodies in the mouth and obtain a measurement and one at 480 seconds to simulate a difficult scan case. It was assumed that the scanbodies were close enough to the posterior to be fully surrounded by the ambient environment of the mouth. It was also assumed that the scanbodies were fastened onto the multi-unit surface by the scanbody screw and thus not expected to shift horizontally or vertically on the multi-unit platform.

The initial temperature (T_0) of the scanbodies was assumed to be the same as the clinic temperature (21° C). For the nominal simulations, the convective heat transfer coefficient (h_c) of forced convection over a bluff object was calculated for each scanbody using the Whitaker Correlation (Eq. 2) and Nusselt number ratio (Eq. 3) [4]. Because clinical airflow conditions may vary, a sensitivity study was also conducted across a range of 5-35 W/(m^2K).

$$Nu = 2 + \left[0.4Re^{\frac{1}{2}} + 0.06Re^{\frac{2}{3}}\right]Pr^{0.4} \quad \textbf{Eq. 2}$$

Where: *Re* is the Reynold's Number and *Pr* is the Prandtl Number.

$$h_c = \frac{Nu * L}{L} \quad \textbf{Eq. 3}$$

Where: *Nu* is the Nusselt number and *L* is the length of the object.

ICamBody	PIC Transfer	Aoralscan ELITE	MicronMapper	T-Marker
34.4 W/(m2K)	28.8 W/(m2K)	23.7 W/(m2K)	36.2 W/(m2K)	31.6 W/(m2K)

Table 2- *Nominal convective heat transfer coefficients h_c calculated for each scanbody tested*

Since dental scanbodies are fastened onto multi-units during measurement, the convective load was applied to all visible faces except for the seating face of the scanbodies. The ambient temperature (T_F) and convective load (h_c) were assumed to be constant throughout the duration of the studies.

To calculate the deformation of the scanbodies in response to the increase in temperature, static studies were linked to their corresponding thermal studies at a timestamp of 90 seconds and 480 seconds respectively. For scanbodies composed of multiple materials, a localized bonded contact was applied at the interface of the two materials. All scanbodies were constrained normal to the seating face in the direction of the multi-unit to prevent them from deforming into the multi-unit. To simulate the fixture of the scanbody screw, the region surrounding the screw channel was constrained perpendicular to the Y-Z and X-Z planes.

Results

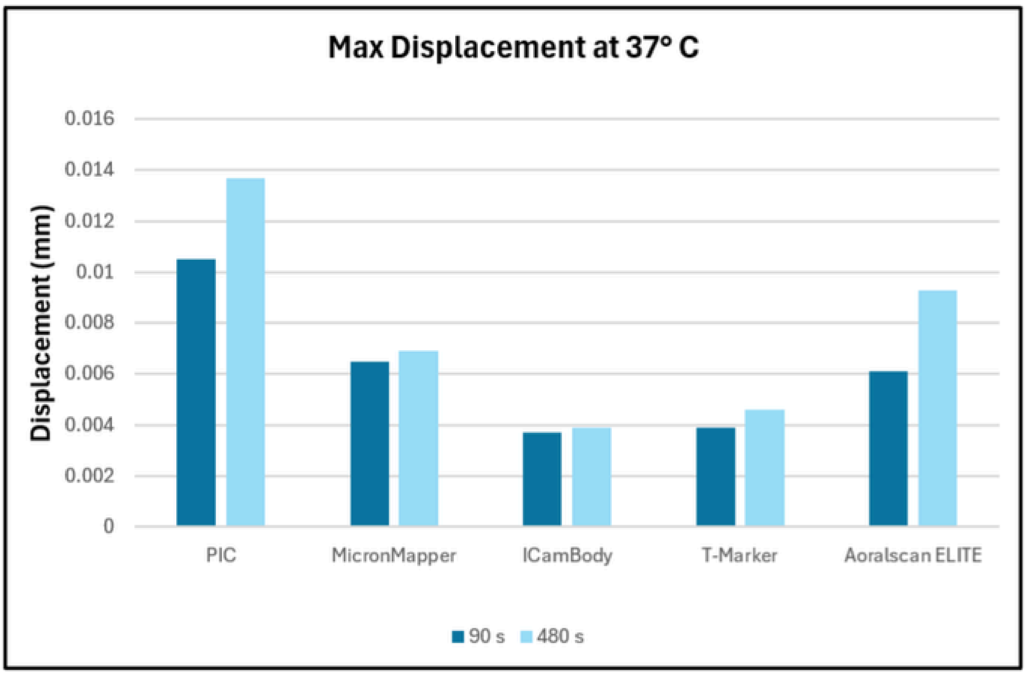


Figure 1

Figure 1 summarizes the maximum displacement due to the applied thermal load at 90 seconds and 480 seconds. As seen in Figure 1, the maximum displacement that occurs is different between the 90-second and 480-second timestamps. This is because at 90 seconds, most of the scanbodies have not yet reached thermal equilibrium and, therefore, have not uniformly reached 37°C. The time-temperature relation of the scanbodies as they approach 37° is summarized in Figure 2 on the next page.

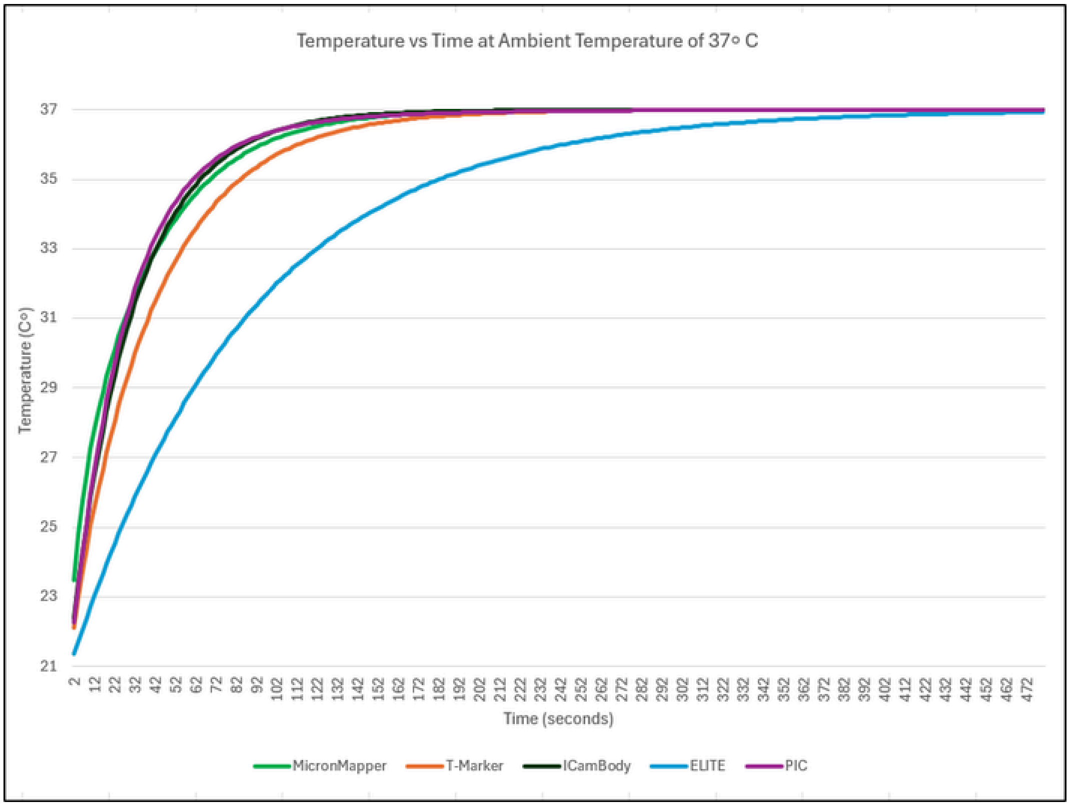


Figure 2-*Temperature-Time Curve as Scanbodies Approach Body Temperature*

Figures 3 and 4 show the resultant displacement for each of the scanbodies at a timestamp of 90 seconds and 480 seconds respectively. The resultant displacement represents the magnitude of the displacement of the nodes in all three directions. The red regions indicate the areas of greatest displacement, while the dark blue regions near the multi-unit seating face indicate displacements close to 0 mm.

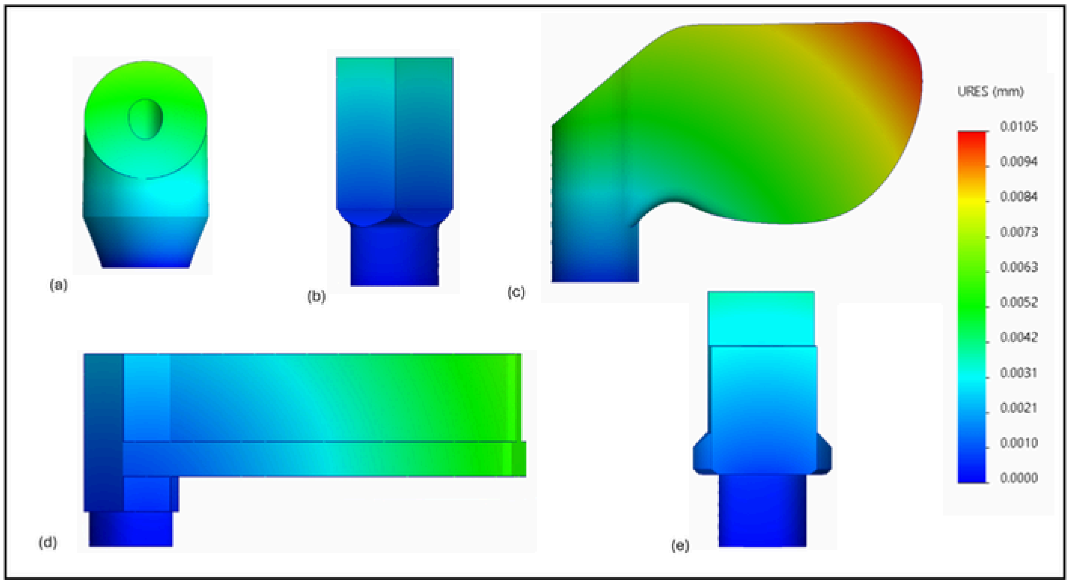


Figure 3- *Resultant Displacement at 90 seconds*

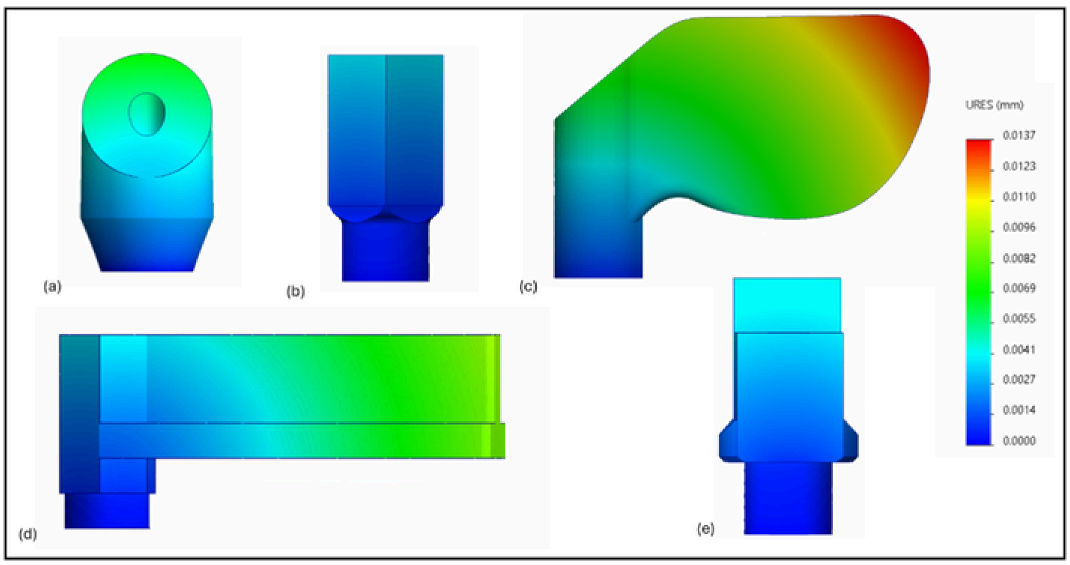


Figure 4- *Resultant Displacement at 480 seconds*

Slight differences are expected between manual linear thermal expansion approximations and simulation results since manual calculations examine expansion in a single dimension only and ignore the geometric complexities of the scanbody design. The percent difference between simulation results of the maximum resultant displacement and manual linear expansion calculations ranged from 0-6.8%.

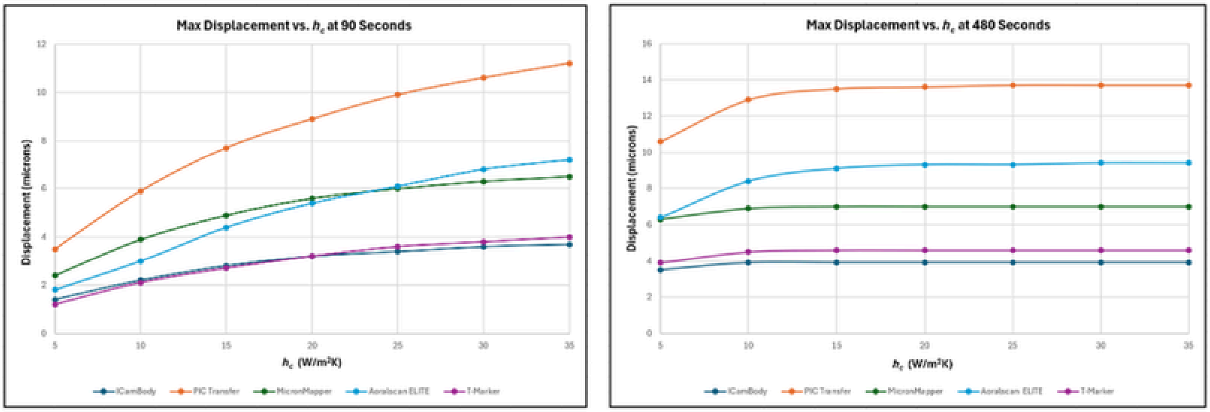


Figure 5- *Expansion vs. convective heat transfer coefficient (h_c)*

Figure 5 summarizes the influence of the convective heat transfer coefficient (h_c) value on the expansion in microns (μm) of the scanbody at a timestamp of 90 seconds and 480 seconds. As seen in Figure 5, the influence of the variable h_c on the resulting expansion is time-dependent. At 90 seconds, variations in h_c resulted in a coefficient of variation percent ranging from 27-37%, indicating that the rate at which the scanbodies approach thermal equilibrium is highly sensitive to the airflow conditions. However, at a timestamp of 480 seconds, the coefficient of variation only ranges from 4-12%, indicating that the maximum displacement of the scanbodies is less sensitive to the value of h_c. This occurs because the scanbodies have had sufficient time to reach or nearly reach thermal equilibrium, regardless of the value of h_c.

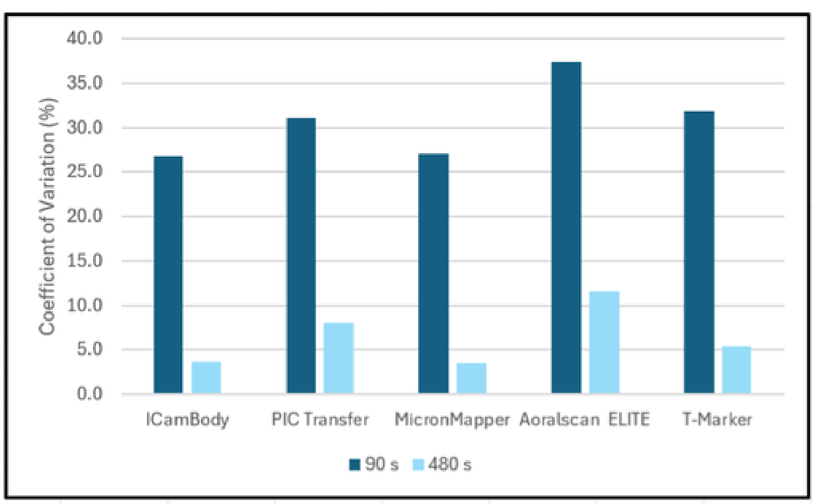


Figure 6- *Percent coefficient of variation of expansion of scanbodies in response to change in convective heat transfer coefficient*

Discussion

As expected, the size and materials of the scanbodies proved to be a significant factor in the amount of deformation experienced. Under nominal ambient conditions (see Table 2), scanbodies with lengths greater than 16 mm (Figure 3c and 3d) demonstrated greater amounts of maximum expansion (6-14 μm) compared to the smaller scanbodies. Scanbodies that are made from PEEK and are larger in size (Figure 3c) showed the greatest amount of deformation at 37°C (14 μm). Of the scanbodies simulated, the ICamBody (Figure 3b and 4b) experienced the least amount of expansion at both 90 seconds and 480 seconds. This is due to a combination of its comparatively small length and use of aluminum and titanium alloys rather than PEEK. Additionally, because of the symmetrical shape of the ICamBody, it also expands relatively symmetrically.

The results in Figures 1- 4 are based on the assumption that scanbodies were uniformly exposed (with the exception of the multi-unit seating face) to the ambient environment of the mouth and the nominal parameters discussed in Table 2. In reality, airflow over a scanbody during oral surgery is very complex and influenced by many factors such as the proximity of the scanbodies to mucosal surfaces and the anterior of the mouth, whether the patient is breathing nasally or orally, and airflow from HVAC and suction. These variations in airflow directly affect the convective heat transfer coefficient (h_c). As seen in Figure 5, at a timestamp of 90 seconds, the largest variances were seen in the PIC Transfer (4-11 μm) and the Aoralscan ELITE scanbody (2-7 μm of expansion). Because of its comparatively smaller size, the ICamBody demonstrated the most consistency in response to changes in h_c, ranging from 1-4 μm of expansion.

A limitation of the existing study is that potential treatments (e.g. anodization, annealing, etc.) of the scanbody materials were disregarded due to lack of available information about the specific treatments the manufacturers use. Heat treatments can help to mitigate the effects of thermal expansion of scanbodies by improving the mechanical properties.

An additional limitation is that as the scanbodies expand, it is challenging to predict how the size and placement of the scan targets will be affected. However, since some scanbodies can expand by as much as 13 μm at body temperature, it is reasonable to assume that the targets have shifted from their original factory-calibrated positions. Especially for measurement devices that are not routinely calibrated prior to use, thermal expansion and the subsequent movement of targets can potentially increase the error between the original factory calibration values and the current implant position measurement. Further studies are needed to determine how much the scan targets shift as the scanbody expands and the impact on the inherent error of each measurement device.

Conclusion

Even at body temperature for a relatively short period of time (90 seconds), dental scanbodies showed an increase in maximum resultant displacement ranging from 4-11 μm under nominal ambient conditions. After reaching thermal equilibrium, these displacement values increased to 4-14 μm. The ICamBody experienced 43-71% less expansion compared to scanbodies that were larger and/or made from PEEK.

Of the many factors that can influence the accuracy of dental measurement systems, the clinical thermal environment alone introduced 1-11 μm of expansion across the range of airflow conditions analyzed in the sensitivity analysis simulations (see Figure 5). The Aoralscan ELITE and PIC system, which both claim measurement accuracy within 5 microns, experienced 6 and 11 μm of expansion, respectively, after 90 seconds of exposure to the nominal ambient environment of the mouth (see Figure 1).

Of the scanbodies simulated, the ICamBody consistently experienced the least expansion at both 90 seconds and 480 seconds, regardless of the applied convective load. This is due to a combination of its comparatively small length and use of aluminum and titanium alloys rather than PEEK. Based on the results from this study and the governing mechanics of thermal expansion, dental scanbody design can be optimized by maintaining a small overall size and using materials with lower CTE values.

Citations

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