Dynamic visco-elastic analysis of silicone maxillo-facial prosthetic material using custom-made dynamic visco-elastometer and LASER measuring device

Original Article

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ABSTRACT

Purpose: The dynamic mechanical properties of silicone maxillo-facial prosthetic material are very important for the successful rehabilitation of patients with facial defects. Moreover, it is equally important to determine these properties under conditions similar to those observed in the natural movement of facial tissues. This study evaluates the dynamic mechanical properties of silicone maxillo-facial prosthetic material using the classical Torsional pendulum method and high precision laser based measurement system. **Materials and Methods:** Five commercially available silicone maxillofacial prosthetic materials A-2002, A-2186, A-VST-50, A-588V-1and MDX4-4210 were taken as sample in the form of cylinders measuring 8X80 mm. A custom-made dynamic visco-elastometer was used to determine the Storage modulus, Loss modulus and Loss tangent over a frequency range of 0.5 to 1.0 Hertz at 37°Celsius. **Results:** A-VST-50, A-588V-1 had low loss tangent (*P* less than 0.05), further they had lower storage modulus than other tested material, which is an added advantage over MDX4-4210 and A-2186. At all test frequencies A-2002 was found to have the highest loss modulus as well as the highest loss tangent (damping factor) among all the five kinds of material tested (*P* less than 0.05) which indicates its slow response to load but large capacity to absorb energy. **Conclusion:** Custom-made dynamic visco-elastometer has proved to be reliable, low cost and a convenient instrument to evaluate silicone maxillo-facial prosthetic material. No single material was found to have all the desirable dynamic mechanical properties necessary for maxillo-facial prosthesis applications. Therefore, layering of two or more such kind of materials is recommended to achieve desirable properties.

KEY WORDS: Dynamic mechanical properties, dynamic visco-elastometer, silicone maxillofacial prosthetic materials

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INTRODUCTION

An ideal maxillo-facial prosthetic material should have dynamic mechanical properties comparable to those of facial and oral tissues to be replaced. Further, as the dynamic mechanical properties are dependent on the excitation frequency, it is equally important to measure them at such frequencies as are expected to occur in real life situations. Under the normal human circumstances the maxillo-facial tissue is subjected to frequencies in the range of 0.5-1 Hz.[12,15] Therefore, it could be useful to determine the dynamic mechanical properties in this range of frequency and hence the torsion pendulum method may be the appropriate method for this purpose

Silicone maxillo-facial prosthetic materials restore the facial defects secondary to treatment of neoplasm, congenital malformation and trauma. Various physical and mechanical properties of silicone maxillofacial

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prosthetic material like tensile strength, tear strength, percentage elongation, shore hardness [1-6] wettability[7] and retention by medical adhesives[8] have been studied.

Silicone elastomers are viscoelastic material because when a sinusoidal stress is applied, they behave neither as perfectly elastic nor perfectly plastic bodies, and the resultant strain will lag behind the stress by an angle, viz., loss angle represented by loss tangent (tan δ). The magnitude of loss tangent depends upon the extent of internal polymer chain motion as well as the imposed excitation frequency. The amplitude of angular deflections was determined for the first and the nth peak. The sensor which records the LASER beam position is flat, and therefore this value needs to be converted into corresponding angular deflection, as shown in [Figure 1] using the following relation:

$$\theta_i = ArcTan\left(\frac{A_i}{2d}\right) \quad (1)$$

The angular oscillation frequency was determined using the relation,

$$\omega = \frac{2\pi}{T} \quad (2)$$

Where, *T* is period of oscillation.

The logarithmic decrement for the damped natural oscillations may now be calculated using the relation,

$$\Lambda_n = \frac{1}{n}\log_e \frac{\theta_i}{\theta_{i+n}} \quad (3)$$

Here, Λ_n is the logarithmic decrement calculated on the basis of *n* oscillations, θ_i is the amplitude of the i^{th} oscillation and θ_{i+n} is the amplitude of the $(i+n)^{th}$ oscillation.

Finally, the material properties of interest are determined using the relations,

$$G_1 = \frac{2LI\omega^2}{\pi a^4}\left(1 - \frac{\Lambda^2}{4\pi^2}\right) \quad (4)$$

and,

$$G_2 = \frac{2LI\omega^2}{\pi a^4}\left(\frac{\Lambda}{\pi}\right) \quad (5)$$

where,

L = length of silicon elastomer sample (meters)
a = radius of silicon elastomer sample (meters)
I = moment of inertia of the inertial discs of the pendulum (Kg- meters^2)
G_1 = storage modulus of the silicon elastomer (N/ meters^2)
G_2 = loss modulus of the silicon elastomer (N/ meters^2)

The storage modulus G_1 is the elastic response and corresponds to completely recoverable energy, whereas the loss modulus G_2 is the viscous response corresponding to energy loss through internal friction. The loss tangent (tan δ) is dimensionless and is equal to the ratio of energy lost (dissipated as heat) to energy stored per cycle.

$$\tan\delta = \frac{G_2}{G_1}$$

The success of rehabilitation using these materials depends very much upon their performance under dynamic conditions. The most relevant dynamic mechanical properties in this regard are the loss modulus, the storage modulus and the loss tangent.[9-11]

The measurement of these properties must be done under conditions similar to those observed in the natural movement of facial tissue.[12] The most relevant parameters in this regard are the frequency and the amplitude of motion.[13] In the past, many researchers have used Dynamic mechanical thermal analysis (DMTA) to determine the dynamic mechanical properties of silicone maxillofacial prosthetic material. Dynamic modulii and resilience were determined using Goodyear Vibrotester for various maxillo-facial prosthetic material and it was concluded that both dynamic and static deformation properties are essential for complete characterization of these materials.[14] Further studies on these materials have been done using wide range of frequency and temperature.[15,16] The most important finding of these studies has been that the dynamic mechanical properties are mostly

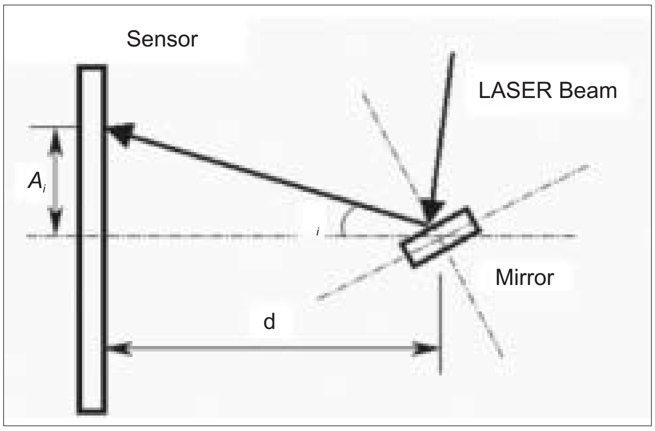

Figure 1: Relation of angular displacement with linear measurement on sensor

Table 1: Typical properties of each silicone test material

Name of test material	Viscosity A cps	Durometer Shore A	Tensile psi	Elongation %	Tear ppi
A-2002*	12,000	25	550	450	75
A- 2186*	90,000	30	900	600	90
A-VST-50*	12,000	30	750	480	112
A-588V-1*	85,000	12	600	700	45
MDX4-4210 0	70,000	27	650	500	90

*(Factor II Inc. Lakeside, Ariz.), 0 (Dow-Corning Corp. Mich.)

insensitive to change in temperature. It was also shown that these properties vary significantly from material to material. DMTA, though accurate, is costly and not accessible in general. Torsion pendulum offers an alternative to DMTA but had not been used for silicone-based materials, probably due to difficulties in achieving adequate accuracy.[17-19]

MATERIALS AND METHODS

Five kinds of room temperature vulcanizing silicone maxillo-facial prosthetic materials were evaluated [Table 1]. Samples were prepared by packing dough into 50/50% stone/ plaster moulds by investing acrylic resin blank cylinder of 8mm diameter and 80 mm length using conventional dental flasking technique. Four samples of each material were prepared in accordance with the manufacturer's processing instructions. All samples were stored in air at room temperature [Figures 2-6].

Experimental setup

To improve the effectiveness of this method, a customized mechatronics system was designed and developed incorporating few innovative features in the conventional design of torsion pendulum, like impulse knob for giving precise impulse without introducing any later oscillations, provision for vertical adjustment of the lower grip for eliminating the axial load, and use of non-invasive and precise measurement system.

The experimental set-up, as shown in [Figure 7], is based upon the fundamental method of measurement of angular motion of the pendulum inertial disc with respect to time. The upper end of the sample (S) is clamped in a grip (1). The grip in turn is fixed to a rod (2), which also carries the circular inertial discs (3). This rod is attached to a wire (4) of known torsional stiffness. The upper end of this wire is attached to an impulse knob (5). The impulse knob is used to give an angular pulse. This specially designed arrangement is capable of giving an angular pulse input to the suspended system, and thus inducing damped free torsional vibrations in the sample, without introducing any unwanted lateral impulse causing lateral oscillations. Slowly turning the impulse knob through a small angle and then bringing it back to original position slowly gives such an impulse. This sets in the torsional oscillations in the specimen and disc assembly, without disturbing the initial mean position of the sample. Without this arrangement an unwanted initial torque would be applied to the specimen changing its torsional behavior.

The vertical rod carrying the upper grip and the inertial discs also carries a mirror (6) for directing the LASER beam from the LASER source (7) to the sensor (8). The mirror is mounted on a special fixture (9), which ensures that the reflecting plane of the mirror is parallel and coincident with the vertical axis of the specimen. The mirror is mounted on this fixture through four adjustable screws, which can be used to obtain such an alignment.

The bottom end of the sample is attached to the lower grip (10). The lower grip is mounted on a vertical rod (11), which carries threads for adjustment of the vertical height of the lower grip. This arrangement is used to ensure that the sample is not subjected to any axial loading due to induced tension in the specimen while tightening it in the grips.

In this manner these special innovative constructional features introduced in a conventional torsion pendulum design ensure that:

1. No torsional loading occurs while mounting or fixing the sample. The sample is subjected to torsional stress only when in motion. This is feasible through adjustment of the impulse knob.
2. The sample is not subjected to any unwanted axial load, either due to weight of the inertial discs or creeping into the system while mounting the sample. This is achieved through adjustment of lower grip in vertical direction.
3. The sample can be kept taut between the grips, by adjustment of lower grip in vertical direction.
4. The initial perturbance through the impulse knob, does not introduce any lateral oscillations.
5. The alignment of the mirror, planar as well as axial, can be done easily using the four mounting screws.

The entire assembly mentioned above is mounted on two circular end plates (12), which in turn are fixed by

Figure 2: Maxillofacial silicone test material: A-2002, A-2186, A-VST-50

Figure 3: Maxillofacial silicone test material: A-588V-1, MDX 4-4210


Figure 4: Proportioning and manipulation of parts of silicone elastomer


Figure 5: Pouring of maxillofacial silicone material in stone mold

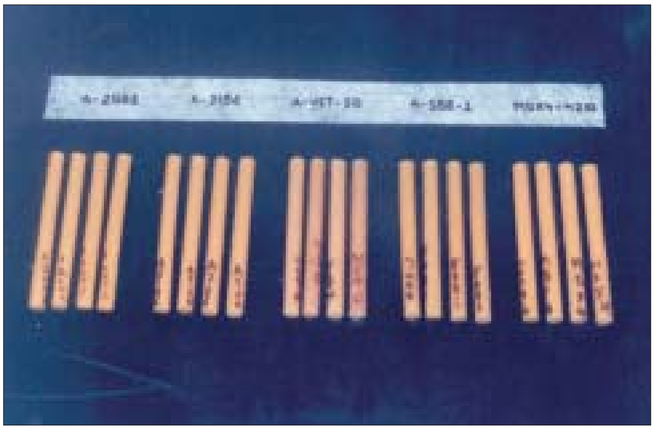
Figure 6: Four cylinder samples of 8x80 mm of five silicone test materials


Figure 7: Dynamic visco-elastometer (Torsional Pendulum Apparatus) with laser measuring device

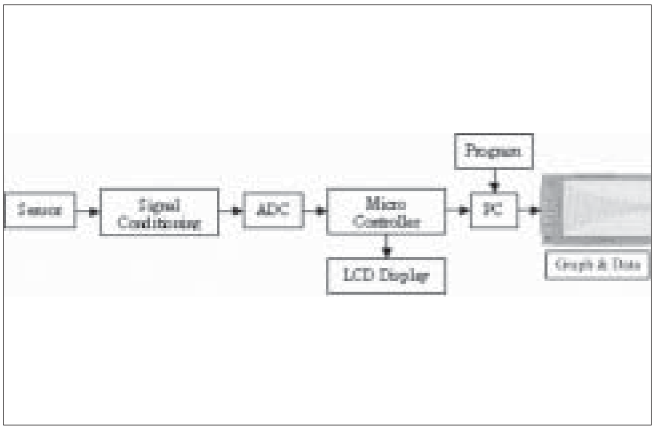

Figure 8: Data flow scheme

three vertical rods (13) using threaded connections. The lower ends of these three vertical rods carry leveling screws (14). Two swing arms (15) are attached at the bottom of this pendulum system, which can be rotated to any angular position in the horizontal plane about the vertical axis passing through the centerline of the sample. These two swing arms carry the telescopic columns (16) for mounting the LASER source and the LASER sensor. These source and sensor are both fixed on their respective platforms (17, 18), supported on the vertical telescopic columns for adjustment of their heights. The telescopic columns can be moved back and forth along the swing arms to adjust the distance of the LASER source and the sensor from the mirror.

The recording and measurement of angular oscillations of the inertial discs is done using a custom-made electronic system interfaced to a PC. The LASER-based measurement system does not introduce any loading on the measurement system, and hence does not interfere at all with the system under motion. Thus, without the loading effect of the measurement system on to the system, the accuracy of measurement is enhanced. Unlike any ordinary source of light, the LASER beam can be focused to a very small size, and is therefore capable of giving high resolution. The resolution and accuracy are further enhanced by the fact that the sensor records the position of peak intensity within the focused beam. The time response of this system is very good due to absence of any mechanical or electrical inertia in the system. All these features of a LASER system have been used to advantage to add to the accuracy of measurement.

A diode LASER is used for generating the beam. The beam is focused on the mirror. The reflected beam is focused on a position sensitive detector. The data from the detector is taken through a serial RS-232C interface. The serial port setting used was 192,000-baud, no parity, 8-bit data and one stop bit. Data is conditioned and fed into an A/D converter. The digital output from the ADC is sent to an 8031 micro-controller using an 8255 interface. Timing and synchronization is achieved through control logic program. Data is communicated to PC through a serial port. A dedicated graphic user interface program was developed to facilitate the operation, data acquisition and plotting of angular displacement as a function of time. The program also calculates the values of peak signal, along with their time, to be used for calculating the dynamic properties of the specimen. The data flow scheme is shown in Figure 8.

Each sample was subjected to a sinusoidal stress deformation, under free damped torsional vibration mode, at three different frequencies by changing the number of inertial discs. Angular displacement of the pendulum was calculated by using basic trigonometric formulae using the measurements of peak displacements recorded on detector sensor using the computer program. Frequency of damped oscillations was also calculated using the data processed on the PC. Finally, the storage modulus (G_1), the loss modulus (G_2) and the loss tangent were calculated using this data. The study for all the samples and all the frequencies was made at 37°C. The frequency range was selected so as to simulate conditions observed in the natural movement of the facial tissue.

RESULTS

Table 2 presents the mean values and standard deviation of storage modulus of five test materials at three different frequencies.

Table 3 presents a two-way analysis of variance (ANOVA) for the data and significant differences between test materials as an effect of increasing frequency and their interaction. Fisher's multiple comparison tests was used to test for significant difference between specific mean values.

At all test frequencies A-2002 had a significantly higher storage modulus than other materials (p less than 0.05) and A-VST-50, A-588V-1 had a significantly lower storage modulus compared to other materials (p less than 0.05), no significant difference was found between A-2186 and MDX4-4210. There was no significant change in storage modulus with increasing frequency [Figure 9]. Table 4 presents the mean values and standard deviation of loss modulus of five test materials at three different frequencies.

Table 5 presents two-way ANOVA for the data and significant differences between test materials as an effect of increasing frequency and their interaction.

Fisher's multiple comparison tests was used to test for significant difference between specific mean values.

At all test frequencies A-2002 had a significantly higher loss modulus compared with other materials (p less than 0.05). There was significant difference in loss modulus with increasing frequency for A-2002. No significant difference was found in loss modulus among A-2186, A-VST-50, A-588V-1 and MDX4-4210 at all frequencies [Figure 10].

Table 6 presents the mean values and standard deviation of loss tangent of five test materials at three different frequencies.

Table 7 presents two-way ANOVA for the data and significant differences between test materials as an effect of increasing frequency and their interaction. Fisher's multiple comparison tests was used to test for significant difference between specific mean values.

At all test frequencies A-2002 had a significantly higher loss tangent compared with other materials (p less than 0.05). There was significant difference in loss tangent with increasing frequency for A-2002. No significant difference was found between A-2186, A-VST-50, A-588V-1 and MDX4-4210 at all frequencies [Figure 11].

DISCUSSION

In the present study frequency range of 0.5 to 1 Hz (pendulum inertia [3.4 –1.8] x 10^{-4} Kgm^2) was selected to simulate the dynamic conditions of facial tissues [12,15] at body temperature because previous studies indicated negligible change in dynamic viscoelastic properties of silicone elastomers over a wide temperature range.[15,16]

Higher storage modulus means higher stiffness. Too large stiffness renders the tissue incapable of absorbing the external disturbance, and a large portion of the external disturbance is transferred to the tissue bed, thus resulting into an irritating sensation. On the other hand, a very low value of stiffness would lead to higher amplitude of oscillations, again causing discomfort.

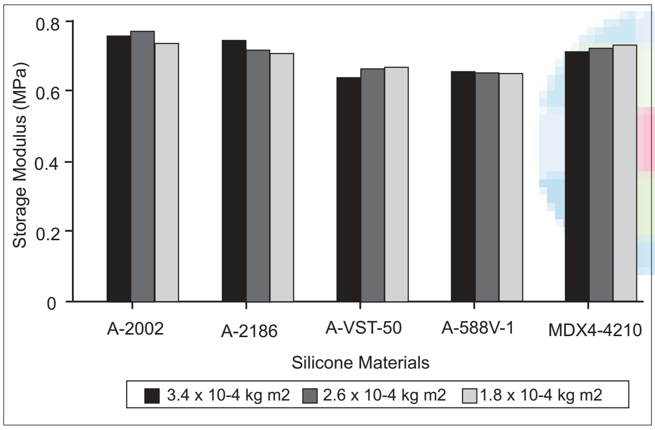

Figure 9: Storage modulus of maxillofacial silicone materials at three different frequencies (pendulum inertia)

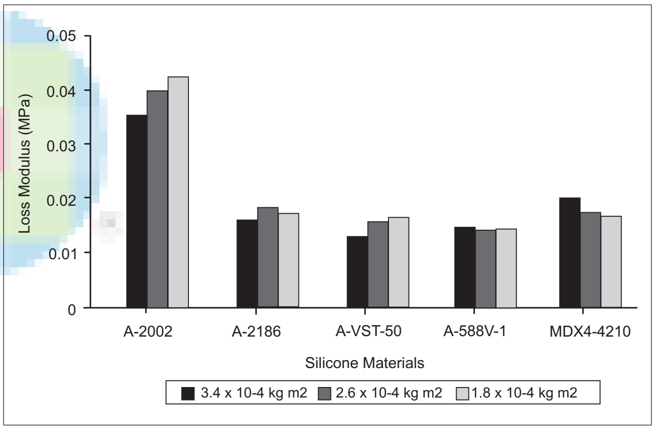

Figure 10: Loss modulus of maxillofacial silicone materials at three different frequencies (pendulum inertia)

Table 2: Storage modulus of maxillofacial silicone materials at three different dynamic loads (Inertia of Pendulum)

Name of test material	Storage modulus (Mean ± SD/MPa)		
	3.4 x 10^{-4} kg m^2 Inertia of pendulum	2.6 x 10^{-4} kg m^2 Inertia of pen dulum	1.8 x 10^{-4} kg m^2 Inertia of pendulum
A- 2002	0.722544 ± 0.0945	0.737531 ± 0.1622	0.704879 ± 0.1672
A-2186	0.711991 ± 0.0727	0.683651 ± 0.1335	0.678491 ± 0.1383
A-VST-50	0.602732 ± 0.0389	0.628396 ± 0.1223	0.636315 ± 0.1308
A-588V-1	0.622927 ± 0.0308	0.620411 ± 0.1201	0.617535 ± 0.1285
MDX4-4210	0.681633 ± 0.0548	0.690525 ± 0.1306	0.698999 ± 0.1419

Table 3: Two way repeated measure ANOVA for storage Modulus G1

Source of variation	d.f.	Sum of square	Mean squares	F ratio	*P* value
Material	4	0.0241	6.025 X 10 -3	42.42	< 0.05
Inertia of pendulum	2	2.760 X 10 -3	1.38 X 10 -3	9.71	< 0.05
Residual	8	1.14 X 10 -3	1.42 X 10 -4		
Total	14	0.0280			

The results, at test frequencies, indicated that A-2186, and MDX4-4210 extra-oral maxillo-facial prostheses silicone elastomers were the stiff material with high storage modulus (high G_1) and low loss modulus (low G_2) with a quick response to load (low damping factor), therefore they had the greatest elastic response to deforming forces. This would suggest a quick return to its original shape, which would seem desirable in reproducing facial tissues. It was found to be in agreement with studies of Water.[15]

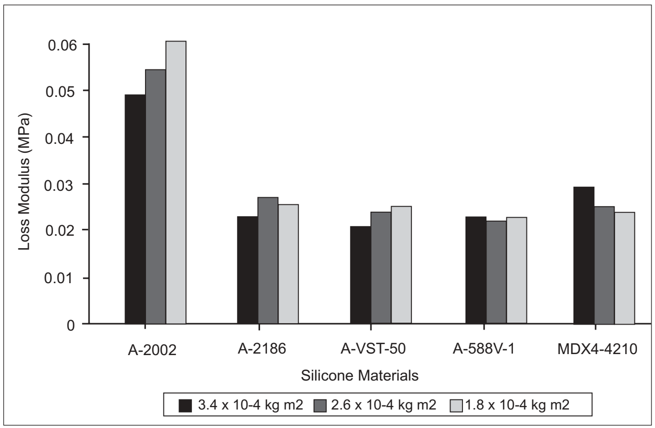

Figure 11: Loss tangent of maxillofacial silicone materials at three different frequencies (pendulum inertia)

It was also observed that newer extra-oral maxillo-facial prostheses silicone elastomers A-VST-50 and A-588V-1 had the same quick response to deformation (low loss modulus G_2 and low damping factor). However less stiff material (comparatively low G_1) could give an added advantage over MDX4-4210 and A-2186 material in being more like facial tissue.

The results at 0.5 – 1 Hz (pendulum inertia [3.4 –1.8] x 10^{-4} Kg-m^2) indicated that newer extra-oral maxillofacial prostheses silicone elastomers A-2002 though having high storage modulus (high G_1) was most resilient because it had significantly higher value of loss modulus G_2 and high value of damping factor (loss tangent) than other four tested silicone elastomers, indicating a slow

Table 4: Loss modulus of maxillofacial silicone materials at three different dynamic loads (Inertia of Pendulum)

Name of test material	Loss modulus (Mean ± SD/MPa)		
	3.4×10^{-4} kg m^2 Inertia of pendulum	2.6×10^{-4} kg m^2 Inertia of pendulum	1.8×10^{-4} kg m^2 Inertia of pendulum
A- 2002	0.033240 ± 0.0061	0.037944 ± 0.0098	0.040215 ± 0.0108
A-2186	0.013921 ± 0.0060	0.016257 ± 0.0057	0.015208 ± 0.0050
A-VST-50	0.010928 ± 0.0028	0.013541 ± 0.0044	0.014358 ± 0.0044
A-588V-1	0.012659 ± 0.0030	0.012014 ± 0.0035	0.012302 ± 0.0036
MDX4-4210	0.018144 ± 0.0067	0.015292 ± 0.0060	0.014678 ± 0.0052

Table 5: Two way repeated measure ANOVA for Loss Modulus G_2

Source of variation	d.f.	Sum of Square	Mean Squares	F ratio	*P* value
Material	4	1.23×10^{-3}	3.075×10^{-4}	1.95	> 0.05
Inertia of pendulum	2	1.56×10^{-5}	7.8×10^{-6}	20.25	< 0.05
Residual	8	1.27×10^{-3}	1.58×10^{-4}		
Total	14	2.52×10^{-3}			

Table 6: Mechanical Loss Tangent of maxillofacial silicone materials at three different dynamic loads (Inertia of Pendulum)

Name of test material	Loss Tangent (Mean ± SD/MPa)		
	3.4×10^{-4} kg m^2 Inertia of pendulum	2.6×10^{-4} kg m^2 Inertia of pendulum	1.8×10^{-4} kg m^2 Inertia of pendulum
A- 2002	0.046557 ± 0.0090	0.052100 ± 0.0128	0.058198 ± 0.0165
A-2186	0.020383 ± 0.0100	0.024473 ± 0.0094	0.022904 ± 0.0082
A-VST-50	0.018170 ± 0.0047	0.021444 ± 0.0066	0.022595 ± 0.0070
A-588V-1	0.020350 ± 0.0050	0.019422 ± 0.0057	0.020116 ± 0.0060
MDX4-4210	0.026903 ± 0.0101	0.022424 ± 0.0092	0.021285 ± 0.0081

Table 7: Two way repeated measure ANOVA for Loss Tangent (tan δ)

Source of variation	d.f.	Sum of square	Mean squares	F ratio	*P* value
Material	4	5.27×10^{-4}	1.31×10^{-4}	8.06	< 0.05
Inertia of pendulum	2	4.47×10^{-4}	2.23×10^{-4}	4.73	< 0.05
Residual	8	8.45×10^{-3}	1.056×10^{-3}		
Total	14	9.43×10^{-3}			

response to deforming load, which would seem to be undesirable in attempting to reproduce the properties of facial tissues. The loss tangent values also indicated the damping factor or energy absorption capacity.[12,15] Although high absorption capacity is not necessarily needed for maxillo-facial material it may be beneficial in areas where maxillo-facial prostheses cover sensitive tissues or bone.[12,15] In this respect A2002 has the higher energy absorption capacity.

The results of dynamic visco-elastic property at all three test frequencies indicated that the storage modulus (G_1), loss modulus (G_2), and damping factor (loss tangent) of the silicone materials increased with increasing frequency. It was found in agreement with the previous studies of Water[15] and Murata.[16]

The results at test frequencies also indicated that loss tangent values ranged from 0.02 to 0.06 of silicone maxillofacial prosthetic materials had almost no viscous component and exhibited elastic behavior. This was found in agreement with study of Murata.[16] However, a wide range of ability in energy absorption was found in the material.

An ideal maxillo-facial prosthetic material should have physical and mechanical properties comparable to those of facial and oral tissues being replaced. However, it appears that ideal material does not exist at present. Knowledge of dynamic viscoelastic properties obtained from this study will assist in characterizing existing materials and may be useful as a reference for future development of maxillo-facial prostheses material.

CONCLUSION

The following conclusions were drawn following evaluation of dynamic visco-elastic properties and statistical calculation of the observations. Custom-designed dynamic visco-elastometer with a laser measuring device proved to be a reliable, low-cost and convenient instrument for evaluation of the dynamic viscoelastic properties of silicone maxillofacial prosthetic material.

A-2002 was found to have the highest loss modulus as well as the highest loss tangent (damping factor) among all the five materials tested which indicates its slow response to load but large capacity to absorb energy. A-2186, MDX4-4210, A-VST-50 and A-588V-1 had the same quick response to deformation (low damping factor), however A-VST-50, and A-588V-1 were less stiff material which might give an added advantage over MDX4-4210 and A-2186 materials in being more like facial tissue.

Significant variation was found in the dynamic visco-elastic properties of the five materials tested. As discussed earlier, only a proper combination of the three properties, viz., the storage modulus, the loss modulus and the loss tangent, would result into higher comfort of the uses. From this point of view none of the five materials was found adequate in all respects. Hence, a need is felt for maxillo-facial material, matching more with the natural human tissue, in terms of dynamic viscoelastic properties. This may be possible through design and development of new materials, or layering of two or more such materials. Experimental investigations may be easily done for the latter option.

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