

Review

Elastomers for maxillofacial applications

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Systematic evaluations of the properties of prosthetic facial materials began to appear in 1969 with a report by Cantor *et al.*¹ They reported that plasticized poly(methyl methacrylate) was the best material with respect to resistance to tearing and degree of elongation. A year later, Walter² reported the specific gravity, water sorption, thermal conductivity, strain in compression, and permanent deformation on an acrylic ester resin, two silicone rubbers and a pourable latex rubber. The laboratory results and clinical trials indicated that the high compressibility and good tissue compatibility of the acrylic polymer made it the choice over the other elastomers.

In 1971, Roberts³ published the physical properties of a heat-cured silicone material and two room-temperature cured silicone elastomers and found tensile strengths from 300–1000 lbs/in², ultimate elongations from 100–350%, tear strengths from 20–100 lbs/in and hardnesses from 45–50 Shore A numbers. The following year, Sweeney *et al.*⁴ determined the properties of a poly(vinyl chloride) maxillofacial material and proposed a set of requirements for such materials including an accelerated aging test for evaluating changes in colour but not mechanical properties.

In 1973 a symposium was held to discuss priorities in dental biomaterials research⁵. At that symposium Castleberry⁶ discussed the choices and challenges of materials for external maxillofacial prostheses. Materials reviewed at that time were poly(vinyl chloride), heat- and room-temperature cured silicones, silphenylene [poly(silphenylene-dimethylsiloxane)], and polyurethanes.

The next year, Lontz *et al.*⁷ reported how the properties of polysiloxanes could be modified by oils and crosslinking agents to approximate the stress-strain profiles of human tissues such as aorta and tendon.

Since 1974 there has been a significant increase in research on maxillofacial materials by Koran and Craig⁸, Goldberg *et al.*^{9–11}, Yu *et al.*¹², May *et al.*¹³, Gonzalez¹⁴, and Koran and co-workers^{15–20}. It is the purpose of this paper to review the developments of maxillofacial materials in the 1970's.

REVIEW

A number of authors have listed the qualities of an ideal maxillofacial material which can be summarized as: (1) having original physical and mechanical properties comparable to human tissue they are replacing, (2) main-

taining these properties during service, (3) being compatible with human tissues and adhesives used to adhere the prostheses to tissues, and (4) being easy to process and insensitive to processing variables.

The stress-strain properties of muscle have been studied by King and Lawton²¹ and Sten-Knudsen²². It has been found that the stress per unit of strain was low and non-linear as well as being more viscous than elastic with the stress-strain curve showing hysteresis. Lontz *et al.*⁷ utilized the above properties of muscle as a basis for modifying a silicone elastomer with oils and crosslinking agents to match the stress-strain properties of tissue in the low strain regions. The information on the viscoelastic properties of soft facial tissues is limited and substantial improvement in its characterization is important in the development of maxillofacial materials.

Until recently only modest efforts had been made in the characterization of the colour parameters of human facial skin. Recently Koran *et al.*¹⁸ measured the colour of 195 whites, 22 blacks and 24 orientals using reflection spectrophotometry. Average reflectance versus wavelength curves for these three groups are shown in *Figure 1* and the

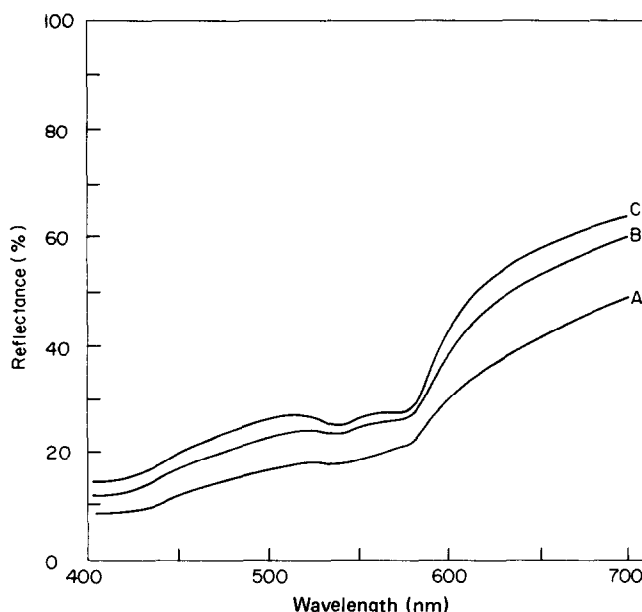


Figure 1 Mean reflectance curves for A, black, B, oriental, and C, white population groups. (Adapted from Koran, A., Powers, J.M., Raptis, C.N. and Yu, R., *J. Dent. Res. Spec. Iss. A*, 1979, 58, 360).

calculated values for luminous reflectance, dominant wavelength and excitation purity are listed in *Table 1*. The wide range of skin colour in each group is indicated by the large standard deviations for luminous reflection and excitation purity. The two peaks at 540 and 580 nm represent the absorption of oxyhaemoglobin and are more pronounced in whites with high values for luminous reflectance and low excitation purity. The curve is lower for orientals and blacks than for whites probably because of greater concentrations of melanin. It is interesting that only minor variations occurred in the dominant wavelength for the three groups. Information of this type is needed for patients who require maxillofacial prostheses, in order to improve the probability of obtaining a proper colour match between the face and the material.

Table 1 Colour parameters for human skin with light source C

	Luminous reflectance	Dominant wavelength, nm	Excitation purity
Blacks	21.9 (7.6)*	588.0 (1.9)	0.360 (0.051)
Whites	30.9 (5.0)	590.7 (3.0)	0.287 (0.036)
Oriental	28.4 (4.0)	588.4 (2.1)	0.320 (0.028)

*Standard deviations in parentheses.

Types of maxillofacial polymers

Commercial and experimental materials include poly(methyl methacrylate), poly(vinyl chloride), chlorinated polyethylene, polyurethanes, and silicones.

Rigid poly(methyl methacrylate) is still used for facial parts such as eyes but the material is hard and does not have an appearance of skin. Low molecular weight oily esters such as the phthalates have been used to plasticize poly(methyl methacrylate) but migration and absorption of stains by the plasticizer are some of the problems with this material and its use as an elastomer is limited. The materials are readily processed in gypsum moulds using standard dough moulding procedures.

Poly(vinyl chloride) is a stiff plastic with a glass transition above room temperature and must be highly plasticized for maxillofacial applications. The polymer yellows on exposure to ultraviolet light and stabilizers must be added in order to minimize colour changes on aging. The polymer is supplied as a finely divided solid suspended in a solvent which when heated results in a sol that gels to an elastomer upon cooling. The processing conditions are critical if optimum properties are to be obtained and the processing temperature indicates the use of metal moulds.

Polyurethanes are polymers produced by the reaction of diisocyanates and polyols. The components are selected such that an elastomer results and the final polymer may contain polyester, polyether, aromatic and/or aliphatic groups. The polyol may be di- or tri-functional depending on whether crosslinking is desired and may be a polyether or polyester macroglycol. The diisocyanate may be either an aliphatic (e.g. hexamethylene diisocyanate) or an aromatic (e.g. tolylene diisocyanate) compound although the former are inherently more stable to ultraviolet light and hydrolytic degradation. The reaction rate may be increased by the use of a curing agent such as stannous

octoate. Finally, both ultraviolet light stabilizers and anti-oxidants may be included. It is apparent that a wide variation in properties may be obtained by the selection of components used to make up the polyurethane. Care must be exercised in the handling of the toxic diisocyanates and the polymerization must be conducted under dry conditions or carbon dioxide will be produced resulting in a porous prosthesis. Processing temperatures of about 100°C allow the use of stone moulds which are more convenient than metal moulds. Finally, since the reaction is stoichiometric the components must be accurately dispensed especially since no extra reactive functional groups are desired in the final polymer.

Silicones of four types have been used commercially or experimentally for maxillofacial materials. Dimethylsiloxane (S-44515) may be vulcanized by heat by using an organic peroxide. This material is cured at 100°C, postcured at 160°C and metal moulds are used. The material is supplied as a high viscosity, rubbery solid and pigments are incorporated using a three-roll rubber mill.

Dimethyl siloxanes (S-382 and 399) having terminal hydroxy groups are available that are polymerized using a stannous octoate catalyst and an orthoalkyl silicate cross-linking agent by a condensation reaction. A highly cross-linked silicone results plus a low molecular weight alcohol from the condensation reaction. Polymerization occurs at room temperature and processing is simple and can be accomplished in gypsum moulds. Microfine silica is used as a filler to improve the physical and mechanical properties.

Dimethylsiloxanes also are available that polymerize by an addition reaction (S-44210). A vinyl terminal siloxane and a silane terminal siloxane are polymerized using a chloroplatinic acid catalyst. The processing is simple and is accomplished at room temperature. These materials also contain microfine silica as a reinforcing agent.

Silphenylene has been used experimentally and is a siloxane copolymer containing methyl and phenyl groups. It is polymerized by a catalyst system similar to S-382 and 399. The material is non-toxic, can be processed in gypsum moulds, may be polymerized from 25–100°C, and has a working time at room temperature of 5 min.

A chlorinated polyethylene also has been developed for use as a maxillofacial material and it has been used clinically. The material may be compounded with other polymers and with pigments on a heated rubber mill and processed in metal moulds at 190°C for 15 min to produce a prosthesis.

Mechanical properties

The original static mechanical properties of commercial and experimental maxillofacial materials are listed in *Table 2*. The properties after accelerated aging for 900 h are also given.

In general the heat vulcanized silicones, the experimental polyurethane and the chlorinated polyethylene had the highest mechanical properties followed by the addition polymerized silicone and the poly(vinyl chloride) and finally the commercial polyurethane. The commercial polyurethane was processed according to the manufacturers directions. Gonzalez¹⁴ has shown that wide variations in properties can be obtained with this urethane by altering the ratio of polyol and diisocyanate and the processing conditions. For example, increasing the diisocyanate component from 11.8 to 13.0% by weight increased the

Table 2 Mechanical properties of polymers for maxillofacial applications

	Ultimate tensile strength, kg/cm ²	Maximum elongation, %	Shear strength, kg/cm ²	Tear energy, ergs/cm ² x 10 ⁶	Tear strength kg/cm	Hardness shore A-F
Poly(vinyl chloride) (Prototype III)						
Original	40.7	215	20.5	4.28	8.9	53
Aged 900 hours ^a	36.2	200	16.9	3.97	—	57
Polyurethane (Epithane)						
Original	8.5	420	15.2	6.67	1.6	6
Aged 900 hours	— ^b	— ^b	— ^b	— ^b	— ^b	— ^b
(Experimental) ^c						
Original	112	500	—	19	—	—
Silicone						
(Silastic 44210)						
Original	42.8	445	24.6	— ^d	16.1	32
Aged 900 hours	39.0	400	24.5	— ^d	—	33
(Silastic 44515)						
Original	59.8	440	26.8	— ^d	—	45
Aged 900 hours	63.2	490	26.2	— ^d	—	45
(Silphenylene)						
Original	98.4	1000	—	—	1.6	35
Chlorinated polyethylene (GSR 1-1)						
Original	94.6	975	—	—	18.8	47
Aged ^e	84.4	950	—	—	13.4	42

^aWeather-Ometer with a 2500 watt Xenon light source with a borosilicate filter to produce an energy spectrum similar to natural sunlight. Water spray was used 18 of every 102 minutes at R.H. of 90% and temperature of 43°C.

^bAging discontinued after 300 h because of degradation of samples.

^cAn aliphatic polyether urethane with an average molecular weight per crosslink of 12900 g/mole and an OH/NCO ratio of 1.1.

^dSamples did not tear but extended as in tensile.

^eAged on rooftop in New Orleans from February to May 1977.

Shore A hardness from 7 to 35. It appears that the manufacturer's ratio causes sufficient unreacted hydroxy groups that a soft urethane results and that increasing the diisocyanate component results in a more satisfactory stoichiometry and a harder urethane polymer. Care must be exercised in proportioning since excess isocyanate groups are undesirable. These results emphasize the critical nature of the proportioning in the processing of urethanes.

The commercial urethane degraded during aging to the point where the material lost its shape after 300 h and thus no mechanical properties after 900 h of aging are reported. The experimental urethane, however, showed no change in tensile strength after 10 weeks in water at 70°C; it also had three times the tear energy after processing compared with the commercial polyurethane.

The silicone materials had minor changes in mechanical properties with the poly(vinyl chloride) and the chlorinated polyethylene showing greater changes. However, except for the commercial polyurethane aging of the polymers does not appear to be a serious problem with respect to mechanical properties.

The dynamic mechanical properties of selected maxillofacial materials have been reported only recently by Koran and Craig⁸. The dynamic modulus determined at a resonant frequency of 60 c.p.s. is plotted as a function of temperature for four materials in Figure 2. The dynamic modulus of all but the room-temperature vulcanized silicone (399) showed a transition at about 0°C with an increase in the rate of change at temperatures below this value. The rate of increase below 0°C was greatest for the poly(vinyl chloride) followed by the polyurethane and the heat-vulcanized silicone (44515). The rapid increase in

dynamic modulus with decreasing temperature for the poly(vinyl chloride) is a drawback for its use in temperate climates.

The fatigue properties of selected maxillofacial materials are listed in Table 3. The samples were strained from 0 to 100% at 60 cycles per minute and the number of cycles to failure was determined. The values for polyurethane have been confirmed by Goldberg⁹ who reported about 10 000 000 cycles to failure for a polyether-aliphatic urethane with an average molecular weight between cross-

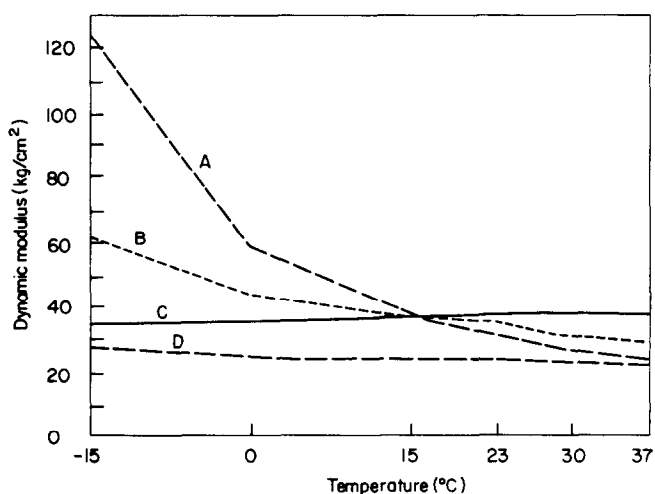


Figure 2 Dynamic modulus as a function of temperature for poly(vinyl chloride) A, polyurethane B, and silicone (Silastic 399 C and 44515 D) maxillofacial materials. (Adapted from Koran, A. and Craig, R.G., *J. Dent. Res.* 1975, 54, 1216).

links of 12 900; these samples were strained from 50 to 150% at 40 cycles per minute. It is apparent that all of the materials except the polyvinyl chloride have acceptable flexural fatigue life.

Again it should be emphasized that insufficient information is available on the static and dynamic properties of human facial tissues to attempt to match these properties with those of maxillofacial materials.

Table 3 Flexural fatigue life of maxillofacial materials

Material	Number of cycles at failure
Poly (vinyl chloride) (Prototype III)	9 000
Polyurethane (Epithane)	9 500 000
Silicone (Silastic 382)	7 300 000
(Silastic 399)	7 000 000
(Silastic 44210)	12 000 000
(Silastic 44515)	11 000 000

Physical properties

Changes in the appearance of maxillofacial prostheses in clinical service suggested that changes in the colour of the polymers may be a significant concern. The colour stability of selected commercially available maxillofacial materials was determined recently by Craig *et al.*¹⁶ The luminous reflectance (comparable to value), dominant wavelength (comparable to hue), and excitation purity (comparable to chroma) were determined after processing and after 900 h of accelerated aging. These three parameters were determined using a reflection spectrophotometer with the sample against a black and white background. Small but significant changes occurred in luminous reflectance after aging for poly(vinyl chloride) with a black background and Silastic 44515 with a white background. A large increase in dominant wavelength resulted from aging the polyurethane for 300 h (yellowing observed with a black background) and a large decrease occurred for poly(vinyl chloride) after 900 h of aging (bleaching of the yellow). The remaining changes on aging for 900 h were slight or not significant.

The results for excitation purity indicate the intensity of colour with higher numbers representing more colour. The low values in Table 4 illustrate the low intensity of colour of the polymers used in maxillofacial prostheses. The decrease in excitation purity for poly(vinyl chloride) shows that a loss of colour occurred on aging for 900 h while the increase for the polyurethane after 300 h indicated an increase in colour. Significant but small changes in excitation purity were observed for the silicone materials after 900 h of aging. The contrast ratio is the ratio of the luminous reflectance with a black background to that of a white background. A ratio of zero represents a transparent material and a ratio of one is a completely opaque material. As seen in the footnotes of Table 4, Silastic 44515 was more opaque than the polyurethane and Silastic 44210, while aging affected the contrast ratio only of poly(vinyl chloride).

These data indicate that the overall colour changes in the basic polymers of maxillofacial materials are minor especially when the practical problems of maintaining aesthetics clinically are considered.

The effect of accelerated aging on the colour of pigmented silicone is shown in Table 5. The addition silicone (Silastic 44210) was selected for evaluation because of its overall superiority in colour stability compared with other materials. The changes in luminous reflectance, dominant wavelength and excitation purity were measured with 11 different pigments at a concentration of 0.2% by weight after 900 h of accelerated aging. The main changes in the pigmented samples occurred in those containing yellow, orange yellow, white, and light orange with small or insignificant changes observed for the other colours. Improvement in white and yellow pigments could contribute to improved colour stability of maxillofacial prostheses and a report by Seluk *et al.*²¹ showed that colour stability of pigments could be improved by sintering them in glass and using the ground glass for pigmentation. However, the changes in colour as a result of pigments were generally small and again could not explain the degree of colour change observed clinically.

From the two previous studies it appeared that the degree of the colour change observed clinically in maxillofacial prostheses may result from staining rather than aging of the polymers or pigments. The stain resistance of a poly-

Table 4 Colour stability of maxillofacial polymers using accelerated aging

	Background	Luminous reflectance		Dominant wavelength		Excitation purity	
		0 h	900 h	0 h	900 h	0 h	900 h
Poly(vinyl chloride) (Prototype III) ^a	Black	7.1	10.3	581.4	501.4	0.252	0.020
	White	66.7	62.9	584.0	583.8	0.552	0.198
Polyurethane (Epithane) ^b	Black	6.2	6.3 ^e	545.0	573.2 ^e	0.008	0.026 ^e
	White	79.6	69.6	583.2	584.0 ^e	0.112	0.164 ^e
Silicone (Silastic 44210) ^c	Black	6.7	6.7	487.0	487.8	0.096	0.090
	White	69.9	78.3	586.0	585.6	0.076	0.106
(Silastic 44515) ^d	Black	8.9	9.5	490.2	489.0	0.102	0.120
	White	60.4	64.5	585.8	586.0	0.252	0.178

^a Contrast ratio at 0 and 900 h 0.11 and 0.16.

^b Contrast ratio at 0 and 300 h 0.08 and 0.08.

^c Contrast ratio at 0 and 900 h 0.08 and 0.09.

^d Contrast ratio at 0 and 900 h 0.15 and 0.15.

^e 300 h of aging since samples disintegrated between this period and 600 h.

(vinyl chloride), an addition silicone and a heat-vulcanized silicone is shown in *Table 6*²⁰. The samples were stained with tea, lipstick and Bismark Brown (disclosing solution) for 24 h. Samples stained with tea or disclosing solution were washed and dried before colour measurements were made. Samples stained with a deep red shade of lipstick were wiped with a clean dry cloth and then cleansed with skin cream until no further stain was visible on the cloth after which they were washed and dried. The changes in luminous reflectance, dominant wavelength and excitation purity before and after removal of the staining agents showed that the three materials had individual staining characteristics. Silastic 44210 resisted staining with tea the best and had good resistance to staining by disclosing solution; it had the greatest change in dominant wavelength with lipstick. The changes in the three colour parameters were much larger than those observed during the aging of the base polymers or the pigmented maxillofacial material. These data confirm that environmental staining is more important than changes in colour from aging of maxillofacial appliances.

Table 5 Change in colour parameters of a pigmented silicone maxillofacial material after 900 h of accelerated aging

Pigment	Δ Luminous reflectance	Δ Dominant wavelength, nm	Δ Excitation purity
White	- 8.7	17.3	0.092
Black	- 0.2*	-0.1*	0.006*
Dark buff	- 0.9	0.1*	0.006*
Medium brown	- 0.4	-0.1*	0.014
Light brown	- 0.6	-0.3*	0.001*
Red brown	- 0.3	-0.3*	0.014
Red	- 0.1*	-2.4	0.005*
Light orange	- 2.7	-0.6	-0.024
Orange yellow	-12.3	-2.7	-0.669
Yellow	-15.0	0.0*	-0.757
Blue	- 0.4	0.7	-0.008

* Difference not significant at the 95% level of confidence.

Table 6 Resistance of maxillofacial materials to various stains for a period of 24 h

	Δ Luminous reflectance	Δ Dominant wavelength, nm	Δ Excitation purity
Poly(vinyl chloride) (Prototype III)			
Tea	- 2.8	- 2.6	+ 0.040
Lipstick	- 5.5	+ 18.9	-0.002
Bismark brown	-36.2	+ 8.3	+ 0.777
Silicone (Silastic 44210)			
Tea	+ 0.6	+ 0.8	+ 0.007
Lipstick	- 5.9	+ 26.5	-0.003
Bismark brown	- 2.0	- 0.2	+ 0.309
(Silastic 44515)			
Tea	- 1.2	+ 0.1	+ 0.026
Lipstick	- 6.9	+ 22.7	-0.042
Bismark brown	- 3.9	0.0	+ 0.377

A study of the cleansing of a stained addition silicone was reported by Yu *et al.*¹⁷. The samples were stained for 24 h by lipstick, Bismark Brown, and methylene blue. The stains were removed by swelling in the following solvents; toluene, benzene, 1,1,1-trichloroethane, or n-hexane for two days. The samples were deswollen by addition of methanol and then dried under vacuum to remove traces of solvents. The luminous reflectance, dominant wavelength,

and excitation purity of the original, stained and cleansed (in n-hexane) samples are listed in *Table 7*. The results with the other three solvents were comparable and thus only the values for n-hexane are shown. It is apparent that solvent extraction of the stains was highly effective. The change in the three colour parameters of the pigmented silicone after cleansing with n-hexane are shown in *Table 8*. Negligible or no change in colour was observed in the pigmented samples after cleaning the samples, indicating stability of pigments after solvent extraction. Also, no significant change in dimensions, of hardness or tensile strength was found between the original and the cleansed samples. These results are encouraging in that the method may be adapted to the cleaning of maxillofacial prostheses that have become discoloured in a service environment.

Table 7 Effect of cleaning of stained silastic 44210 on colour parameters

Stain	Luminous reflectance	Dominant wavelength, nm	Excitation purity
Lipstick			
Original	84.3	584.5	0.078
Stained	77.1	613.9	0.063
Cleaned	83.6	584.7	0.076
Bismark brown			
Original	83.9	584.6	0.078
Stained	77.7	584.4	0.596
Cleaned	84.4	584.5	0.081
Methylene blue			
Original	85.0	584.2	0.076
Stained	78.6	581.2	0.069
Cleaned	85.5	584.2	0.079

Table 8 Change in colour parameters of pigmented silastic 44210 after extraction with n-hexane

	Δ Luminous reflectance	Δ Dominant wavelength, nm	Δ Excitation purity
White	-0.5	+ 1.7	+ 0.029
Black	-0.1	+ 0.5	0.000
Dark buff	-0.4	+ 0.1	+ 0.001
Medium brown	-0.1	+ 0.1	0.000
Light brown	-0.5	+ 0.2	+ 0.003
Red brown	-0.2	+ 0.2	+ 0.002
Red	0.0	+ 0.1	-0.012
Light orange	+ 0.1	+ 0.2	0.000
Orange yellow	-0.3	+ 0.1	-0.001
Yellow	-0.4	0.0	+ 0.001
Blue	-0.1	+ 0.2	0.000

Current status and future developments

Ease of manipulation and processing favour the selection of a room temperature polymerized silicone which can be processed in an easily constructed gypsum mould. Silicones of the 44210 type have the advantage over the 382 and 399 types as well as the silphenylene type in that no volatile by-product is formed during polymerization and thus the former are more dimensionally accurate. The processing of the poly(vinyl chloride) materials is exacting and metal moulds must be used because of the high processing temperatures required. The proportioning of the components of the polyurethanes is highly critical since the reaction is stoichiometric and no residual isocyanate groups should remain since they are very toxic. For this reason, the

diisocyanates must be handled with caution. The polyurethane must be processed under dry conditions and metal moulds are required. The processing of chlorinated polyethylene is done at high temperatures in a metal mould.

Although the room-temperature polymerized silicone 44210 did not have as high static mechanical properties as the experimental polyurethane and the chlorinated polyethylene, the values are similar and more than adequate. The stability of the dynamic modulus of silicone 44210 as a function of temperature is also desirable in a service environment since it will have the same stiffness at very low and high temperatures.

Properly stabilized maxillofacial polymers show minor changes in colour with accelerated aging. Pigmented polymers also show no major changes in colour although specific white and yellow pigments may demonstrate small changes in colour as a function of time of aging. The large changes in appearance of maxillofacial prostheses results from staining as a result of environmental stains, body oils, or cosmetics applied by the patient.

Highly crosslinked polymers such as the silicone 44210 can be cleaned by solvent extraction without altering the physical and mechanical properties. This type of cleaning is not possible with the plasticized poly(vinyl chloride) or the chlorinated polyethylene. Solvent cleaning techniques will add to the service life and aesthetics of the prosthesis.

Additional information needed to improve maxillofacial materials is further definition of the mechanical properties of human tissues with respect to their elastic and viscoelastic properties. This information should permit a better matching of the properties of the prosthesis to the tissues which it is replacing.

The range of colours of the face have been reasonably well documented by reflection spectrophotometry. It should now be possible to formulate the matching base colour for a prosthesis by measuring the skin colour of a patient with a spectrophotometer and subsequently using a computer program to specify the ratio of specific pigments and elastomer to match the specific skin colour. The application of this information should result in improved aesthetics after final characterization of the prosthesis with a considerable saving of clinic time.

Another area of investigation which should receive attention is a study of adhesives and their effects upon the tissues and the maxillofacial materials.

It is apparent that based on existing knowledge, room-temperature polymerized silicone polymers of the addition type (44210 being a commercial example) offer optimum overall properties for maxillofacial applications.

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REFERENCES

- 1 Cantor, R., Webber, R.L., Stroud, L. and Ryge, G., *J. Prosth. Dent.* 1969, **21**, 324
- 2 Walter, J.D., *Dent. Practit. Dent. Record* 1970, **20**, 208
- 3 Roberts, A.C., *Dent. Practit. Dent. Record* 1971, **21**, 276
- 4 Sweeney, W.T., Fisher, T.E., Castleberry, D.J. and Cowperthwaite, G.F., *J. Prosth. Dent.* 1972, **27**, 296
- 5 Wachtel, L.W., (Ed.) *'Proceedings Symposium — Dental Biomaterials — Research Priorities'*, Department of Health Education Welfare Publication No. (NIH) 74-548, Washington, D.C., 1974, 275 pp
- 6 Castleberry, D.J., *'Proceedings Symposium — Dental Biomaterials — Research Priorities'*, Department of Health Education Welfare Publication No. (NIH) 74-548, Washington, D.C., 1974, p 255-62
- 7 Lontz, J.F., Schweiger, J.W. and Berger, A.W., *J. Dent. Res. Spec. Iss.* 1974, **53**, 277
- 8 Koran, A. and Craig, R.G., *J. Dent. Res.* 1975, **54**, 1216
- 9 Goldberg, A.J., *'Polyurethane Elastomers as Maxillofacial Prosthetic Materials'*, Doctoral Dissertation, University of Michigan, Ann Arbor, 1977, 194 p
- 10 Goldberg, A.J., Craig, R.G. and Filisko, F.E., *J. Dent. Res. Spec. Iss. A* 1977, **56**, A173; and *Dental Materials Group Microfilm*, IADR, Copenhagen, 1977, paper 523
- 11 Goldberg, A.J., Craig, R.G. and Filisko, F.E., *J. Dent. Res.* 1978, **57**, 563
- 12 Yu, R., Koran, A. and Craig, R.G., *J. Dent. Res. Spec. Iss. B* 1977, **56**, B150; and *Dental Materials Group Microfilm*, AADR, Las Vegas, 1977, paper 392.
- 13 May, P., Guerra, L.R. and Rauls, H.R., *J. Dent. Res. Spec. Iss. B* 1977, **56**, B150; and *Dental Materials Group Microfilm*, AADR, Las Vegas, 1977, paper 394
- 14 Gonzalez, J.B., *J. Prosth. Dent.* 1978, **39**, 179
- 15 Yu, R., Koran, A. and Craig, R.G., *J. Dent. Res. Spec. Iss. A* 1978, **57**, 295; and *Dental Materials Group Microfilm*, IADR, Washington, D.C., 1978, paper 881
- 16 Craig, R.G., Koran, A., Yu, R. and Spencer, J., *J. Dent. Res.* 1978, **57**, 866
- 17 Yu, R., Koran, A., Raptis, C.N. and Craig, R.G., *J. Dent. Res. Spec. Iss. A* 1979, **58**, 360
- 18 Koran, A., Powers, J.M., Raptis, C.N. and Yu, R., *J. Dent. Res. Spec. Iss. A* 1979, **58**, 360
- 19 Koran, A., Yu, R., Powers, J.M. and Craig, R.G., *J. Dent. Res.* 1979, **58**, 1450
- 20 Koran, A., Powers, J.M., Lepeak, P.J. and Craig, R.G., *J. Dent. Res.* 1979, **58**, 1455
- 21 King, A.L. and Lawton, R.W., *'Elasticity in Body Tissues'*, in *'Medical Physics'*, (Ed. O. Glasser) Vol. II, Year Book Publishers, Chicago, 1950, p 303
- 22 Sten-Knudsen, O., *Acta Physiol. Scand.* 1953, **28**, Suppl. 104
- 23 Seluk, L.W., Yu, R. and Koran, A., *J. Dent. Res. Spec. Iss. A* 1979, **58**, 361