Creep and Viscoelastic Behaviour of Human Dentin

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Statement of Problem: Biomechanics of the human dentition is inherently complex.
Purpose: The aim of this study is to investigate, in vitro, the creep and the recovery of dentin under static uniaxial compressive stress conditions.
Materials and Methods: Specimens of cylindrical morphology were prepared from recently extracted non-carious lower molar teeth, such that the average tubule orientation was axial. Slides of mid- coronal dentin (parallel surfaces, height 1.8 mm) were sectioned with a slow speed diamond saw and then cut into cylindrical discs. Specimens were stored at 4ºC for 24h to restabilize water content. Creep data were then measured by LVDT axially in water for periods of 2h load + 2h recovery on 4 separate groups (n=6): at two stresses (10 & 18 MPa) and at two temperatures: 37 & 60ºC. Maximum creep strain, permanent set, strain recovery and initial compressive modulus were reported.
Results: Compliance values were also calculated and slight non-linearity found at 60ºC. Two-way ANOVA was performed on results. Dentin exhibited a linear viscoelastic response under 'clinical' compressive stress levels, with a maximum strain ~ 1% and high recoverability: permanent set<0.3%.
Conclusion: This established a performance standard for viscoelastic stability of restorative biomaterials, replacing human dentin.

Key Words: Creep- Viscoelastic property- Dentin

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The mechanical properties of dentin and enamel involving stress-strain relations due to tension, bending and shear have been investigated under quasi-static conditions. Modulus and proportional limits have been deduced from linear time-dependent stress-strain curves and deviations from their linearity have been reported for teeth subjected to compressive forces. (1)

The difficulty, however, in understanding thoroughly the mechanical properties of dentin has been related to the existence of the two phases of the tissue with very different properties. The Young's modulus E_d, of dentin has been expressed by the Voigt model in terms of the two phases as: $E_d = E_A V_A + E_C V_C$ (1)

Where $E_A V_A$ is the product of the Young's modulus for the pure apatite phase and the volume fraction of the apatite phase in the dentin, and $E_C V_C$ is the similar product for the collagen phase. However, a modification of this model into a four-element mechanical model helps in the conceptual understanding of the response pattern of a viscoelastic material in both the loading and recovery phases.(2) Some of the theoretical models that have been proposed to predict the mechanical behaviour of hard tissues like bone, enamel and dentin include the Hashin spherical particle model and the Voigt, Ruess and Hashin- Shtrikman models;(3) with the latter predicting only the upper and lower limits of the elastic moduli of the hard tissues. Mathematical models of viscoelasticity have been compared with experimental findings and demonstrate that the stress response of human dentin is consistent with linear viscoelasticity models.(4)

The earliest systematic measurements investti-gating the compressive behaviour of dentin was reported by Black,(5) who concluded that neither the location nor the orientation of the tubules of the test specimens made much differences. However, later attempts to confirm or disprove this assertion were obscured by certain limitating factors in the testing procedures.(6) Stanford and coworkers initially reported that dentin exhibited anisotropy with regards to the orientation of the tubules,(7) but this report could not be verified in a more extensive investigations carried out later(8) Dentin was reported to exhibit viscoelastic behaviour as a result of the high proportion of organic material and water present in it, as well as the viscoelasticity of collageneous tissues.(9)

Viscoelastic data obtained from the compressive properties of dentin is particularly important in the process of mastication since masticatory forces include a compressive component.

The aim of this study was to determine the viscoelasticity of human dentin under the action of a uniaxial static compressive stress.

Materials and Methods

Recently 24 extracted non-carious lower molar teeth were used. Cylindrical specimen was prepared from a plane parallel slice of coronal dentin. This process was required in order to obtain maximum specimen volume and uniform radial orientation of dentinal tubules within each specimen and from specimen to specimen. It was ensured that the tubules were aligned as near as possible, perpendicular to the specimen surfaces. First, slices of mid-coronal dentin (~2 mm) were made by a slow speed diamond. Then, the specimens were gently ground flat using wet 600 grit carborundum papers in order to obtain specimens with height of 1.80±0.01 mm. The two ends of the initial slices were parallel and smooth. Circular cylinders of dentin were thus produced with the following average dimensions: diameter, d=3 mm and height, h=1.8 mm. The surface area and the heights of the specimens were measured using a set-up comprising a light microscope connected to camera and PC having HpImage software for image capture. Area measurements were made by SigmaScan software (Jandel Scientific, Germany) on each dentin specimen immediately before and after each test to evaluate all dimensional changes that might occur after stress application.

Figure1 shows the configuration and orientation of the specimen with respect to the entire teeth. In order to avoid the problems of cutting small specimens from the tooth without damaging them either mechanically or thermally, each specimen was cut using a straight No.731 M fissure bur with a high speed handpiece and copious water spray. The two ends of each cylindrical specimen were parallel and smooth. Prepared specimens were checked under the microscope, and any defective specimen was discarded. The prepared specimens were stored in distilled water for 24 hours prior to test to permit re-stabilization of the water content of dentin without causing any changes in its elastic properties.(10)

Specimen allocation

Specimens were divided into two groups on the basis of different applied stresses (10, 18 MPa) and each group divided into two different subgroups based on two different test temperatures: 37 and 60°C. Each group (n=6) of specimens was then stored in labeled plastic tubes containing fresh refrigerated distilled water in the fridge. Each experiment consisted of the application of a constant uniaxial compressive stress, recording of uniaxial creep strain of the specimen for 2h, release of the stress and recording of the recovery strain for 2h.

Equipment:

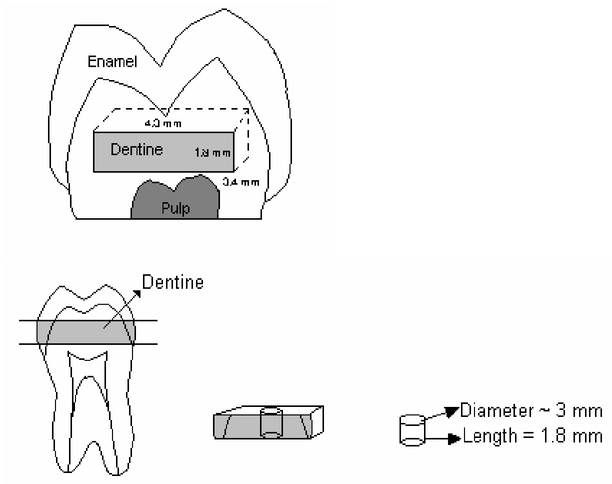
A creep measurement apparatus was fabricated in the Biomaterials Science Unit. It was designed to subject a test specimen, e.g. dentin specimens, to static uniaxial compressive stresses of 10 and 18 MPa for a period of 2 hours followed by 2 hours of strain recovery when the load was removed. The apparatus had an inverted U-shaped steel base comprising a lever, L, pivoted at one end by means of a bearing pin on a vertical pillar. A loading pin, P, which was 1 cm in diameter was held in a reduced friction bearing, B, and was vertically located such that the limited angular motion of the lever produced a linear displacement of the pin in a vertical plane. A raised platform in axial alignment with the loading pin accommodated the test specimens such that application of the standard weights, M, at the end of the lever ensured compressive forces were coaxially directed onto the specimen, S.

The complete creep apparatus had a water-bath constructed from an acrylic tube, which surrounded the specimen platform and sat on the steel base. The bath was connected by two rubber tubes to a variable temperature-controlled water-pumping unit, which provided the thermal equilibrium at a selected temperature (Fig. 2).

Each experiment consisted of the rapid application (<2 s) of a constant compressive stress, with recording of the uniaxial creep strain of the specimens for two hours. After 2 h, the stress was released and recording made of the recovery strain for two hours. The magnitudes of the applied stresses in separate runs were 10 and 18 MPa, which were well below the yield strength of the dentin. The unloading phase of the test was achieved by carefully raising the lever (which supports the load), off the loading pin, P, which was then supported horizontally with a rigid beam.

The measurement involved assembling the specimens on the platform of the creep apparatus in the water-bath. The start of the data acquisition was triggered, after placing the specimen to equilibrate in the testing environment for about 10 minutes.

The time-dependent compressive strain at 10 and 18 MPa was obtained for 2 hours loading period followed by 2 hours of stress-free phase.



A B C

Fig. 1- A) Diagrammatic representation of the tooth showing the location from which the dentin specimen was removed **B)** slice of dentin **C)** specimen.

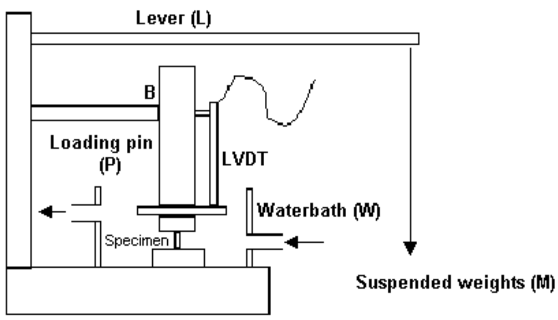


Fig. 2- Schematic diagram of creep measurement apparatus

Data was obtained on six dentin specimens each under the two compressive forces at the two clinical temperatures of 37°C and 60°C.

Visco-elastic theory

The superposition principle is the basis for the linear viscoelastic theory. Ludwig Boltzmann in 1874 put forward his superposition principle, which has formed a sound basis for subsequent theory. The principle is considered here as it is applied to the stress relaxation and creep properties of solids.[11,12] In a mechanical creep experiment, a stress, s_o, is applied to the specimen rapidly at time t = 0, and then held constant till time t = t_1, when the stress is removed. Specimens exhibit permanent set when, after removal of stress, strain does not return ultimately to zero. The vast majority of solids studied at small strains confirm the superimposition principle, or at least there is a critical strain below which this principle holds.

Two major postulation in the linear superimposition principle are as follows:

1- The resulting strain imposed on specimens will bear the same ratio as stress, if strain is measured at the same time after application of stress. This ratio is termed the compliance, ?(t).

2- A linear superimposition of strains will occur in a material for concurrently running creep experiments which are triggered off at different times.

For solids, such as polymers, undergoing creep, a time-dependent compliance, ?(t), may thus be defined, ie:

$$J(t) = \frac{e(t)}{s_0} = \frac{1}{E(t)} \quad (2)$$

Where e (t) is the time-dependent strain and E is the elastic modulus. Consider a cylindrical/disc-shaped specimen to which a step stress is applied, s_o, at time t = u, the resulting compliance is:

$$J(t) = J_u + (J_R - J_u)\Psi_s(t) \quad (3)$$

Where J_u is the instantaneous elastic compliance and J_R is the final (infinite time) or anelastic compliance. The time function ? (t), is a normalized creep function that varies between 0 and 1 (Fig. 3).

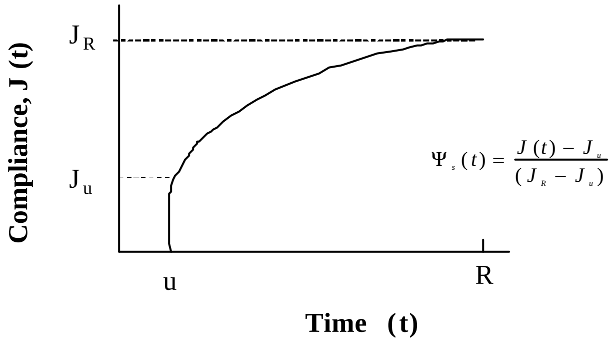


Fig. 3- Creep compliance versus time curve for a visco-elastic material showing the relationship between the compliance parameters, J_u, J_R and the creep function (t).

For the single relaxation/retardation model [SRT], (t) is expressed as:

$$\Psi_s(t) = [1 - \exp(-t/t_s)] \quad (4)$$

Where t_s is the retardation time-constant at constant stress of s. The resulting different equation which relates (t) and (t) for the special case of a single retardation [SRT] is obtained as:

$$t_s \frac{de(t)}{dt} + e(t) = t_s . J_u \frac{dt(t)}{dt} + J_R . s(t) \quad (5)$$

Solving equation (5) particularly for static creep, where the stress level is constant at s_o, ds /dt=0, gives the relation:

$$\frac{J(t) - J_u}{(J_R - J_u)} = (1 - e^{-t/t_s}) \quad (6)$$

Which is equivalent to equation.[3] Boltzmann's superposition principle, therefore, indicates the response of a specimen that experiences either an arbitrary stress history, or an arbitrary strain history (the corresponding argument is for stress-relaxation experiments). This generalizetion formed the basis for the linear viscoelastic theory.

Creep

Under the influence of a constant stress, materials can deform permanently if a load is applied for a long time, even though the stress on the material may well be below its elastic limit. This time-dependent deformation of materials is known as creep. Typical creep curves and different stages of deformation will be discussed later.(13)

Three stages can be identified and distinguished from the overall curve of creep-strain as a time function (Fig. 4). These are typical of any viscoelastic material. This curve type is characterised by an initial rapid deformation showing a Hookian elastic behaviour at lower stress levels, followed by a viscoelastic (anelastic creep) stage which is non-linear in time. After releasing the stress, there is an initial recovery phase followed by an irreversible viscous strain. This is referred to as the permanent set.

Results

The experimental results evaluated from the compressive strain-recovery curves of dentin are presented in Table I. Also, it shows some of the creep variables such as the maximum creep strain, $\mathbf{Y_m}$, the permanent set, $\mathbf{E_s}$, strain recovery, $\mathbf{Y_r}$, and the initial compressive modulus, **E**, evaluated from the data obtained. The statistical quantities (mean, standard deviations) as well as the coefficient of variation (CV%) of these creep variables are presented in Table I. Examining the standard deviations for human dentin displays larger standard deviations compared to dental restorative composites. As a biological tissue this is not surprising due to the variations in the calcification and structural integrity of its components. Figure 5 represents the compressive creep strain, e, curves. Figure 6 illustrates the compliance, **J(t)**, curves as time functions and each curve represents the mean of six graphs obtained from six dentin samples.

Maximum Creep Strain, Y_m:

A two-way analysis of variance (ANOVA) was used to compare and evaluate the maximum creep data of dentin specimens at different conditions of stress and temperature (10/18 MPa, 37/60°C). Hight significant differences were found between 10 and 18 MPa ($P<0.01$). In addition, there was a high significant difference between the data for the two temperatures (37 and 60°C) ($P<0.01$). The interaction term for temperature and stress was not significant ($P= 0.07495$). An average of maximum creep strain of 1.58% was evaluated when a compressive stress of 18 MPa was applied at 60°C. The average of the Y_m value at 37°C (wet) at the same stress level was 1.18%. The lowest Y_m value was 0.97% with 10 MPa compressive stress. There was an increase trend in maximum strain with increasing the temperature or stress. Specimens deformed progressively with time under the constant compressive/ stresses applied. The magnitude of the deformation increased from the lower to the higher stress level.

Permanent Set, E_s

Releasing the compressive force on a material that is deformed within the elastic region results in a 100% strain recovery. For a material e.g. dentin undergoing viscoelastic deformation, an irrecoverable strain referred to as a permanent set, E_s, occurred. A two way analysis of variance (ANOVA) did not show significant difference in permanent set between the two different stress levels (10, 18 MPa) ($P= 0.12207$), whereas this test revealed highly significant differences between data for the two different temperatures (37, 60°C) ($P<0.01$). The interaction term in this test was not significant ($P= 0.276$). The maximum value of the permanent set (0.47%) was observed at 60°C when 18 MPa compressive stress was applied. This was followed by the value of 0.33% at the same temperature upon the application of 10 MPa compressive stress. The least E_s value was 0.26% when a compressive stress of 10 MPa was applied at 37°C and approximately similar to the value of 0.28% obtained from a compressive stress of 18 MPa at 37°C.

Table I- The maximum strain, permanent set, strain recovery, initial compressive modulus, area before and after test and thickness of samples

Condition Stress/Temperature (MPa/°C)		**Maximum Strain Y_m (%)**	**Permanent Set E (%)**	**Strain Recovery Y_r (%)**	**Thickness (mm)**	**Initial creep modulus E (GN/m2)**	**Area before test mm^2**	**Area after test mm^2**
10 MPa/ 37°C	**Mean**	0.97	0.26	72.41	1.8	12.54	7.04	7.005
	SD	0.15	0.04	6.35	0.03	2.15	0.10	0.17
	CV%	15.01	15.03	8.77	1.81	17.12	1.48	2.49
10 MPa/ 60°C	**Mean**	1.08	0.33	69.32	1.78	12.21	7.23	7.25
	SD	0.20	0.09	6.26	0.05	0.73	7.17	0.40
	CV%	18.19	28.21	9.03	2.80	5.97	7.19	5.48
18 MPa/ 37°C	**Mean**	1.18	0.28	76.64	1.81	17.64	6.94	6.94
	SD	0.04	0.04	2.95	0.04	1.68	0.29	0.27
	CV%	3.6	15.35	3.85	2.28	9.51	4.22	3.86
18 MPa/ 60°C	**Mean**	1.58	0.41	73.41	1.79	14.71	6.91	6.91
	SD	0.28	0.09	6.21	0.04	1.84	0.41	0.42
	CV%	17.41	21.36	8.46	2.1	12.52	5.94	6.03

Creep Strain Recovery (Y_r)

As a result of the irrecoverable strain occurring in dentin after releasing the compressive force, strain recovery (Y_r) was in the range of 60% to 80%. There was no significant difference between creep-recovery of two different stresses (10,18 MPa) (P= 0.85). The same result was found between creep strain recovery for two different temperatures (37, 60°C) (P=184).

Initial compressive modulus (E)

The initial compressive modulus is the ratio of stress to strain within the first 20 seconds, s /e, which was determined from creep-strain data obtained on the dentin specimens when stressed within the elastic region. A two-way analysis of variance (ANOVA) showed highly significant difference in this modulus between the two different stress values (P<0.01), and significant difference between two different temperatures (P<0.05). There was no interaction between the variables of temperature and stress (P= 0.0741).

The highest value (17.64 GPa) obtained by compressing cylindrical specimens of dentin was 18 MPa compressive force at 37°C, whereas the lowest value (12.21GNm^{-2}) was obtained at 60°C by compressing dentin with 10 MPa stress.

There was an increase in the initial compressive modulus with decreasing temperature.

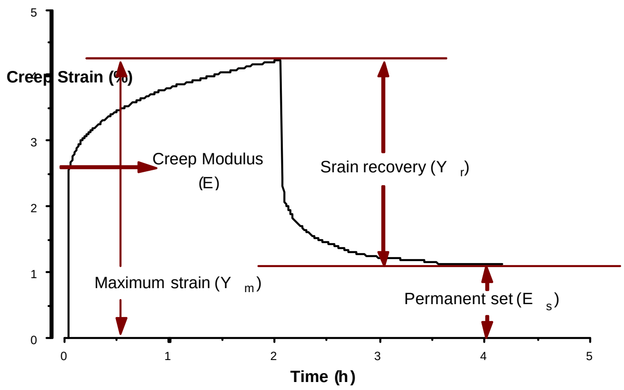


Fig. 4- Schematic representation of time-dependant strain deformation and recovery curves of a viscoelastic material under a constant compressive stress

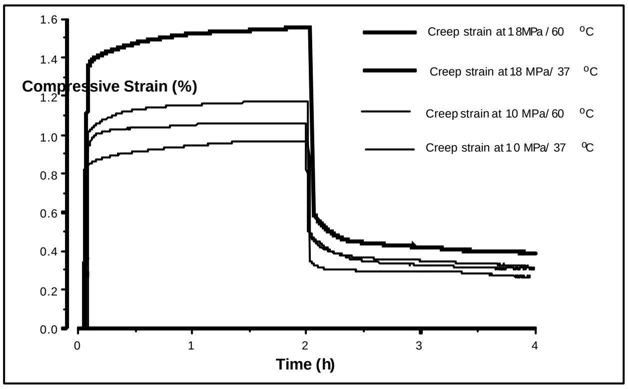


Fig. 5- Compressive creep behaviour of dentin at two temperatures (37,60 °C) during 10 and 18 MPa compressive stresses

Creep compliance J(t):

Creep compliance, **J**(t), **J**(t)= 1/**E**(t) and recovery curves for dentin are presented in figure 6. It shows the creep compliance behaviour of dentin upon the application of 10` and 18 MPa compressive forces at two different temperatures.

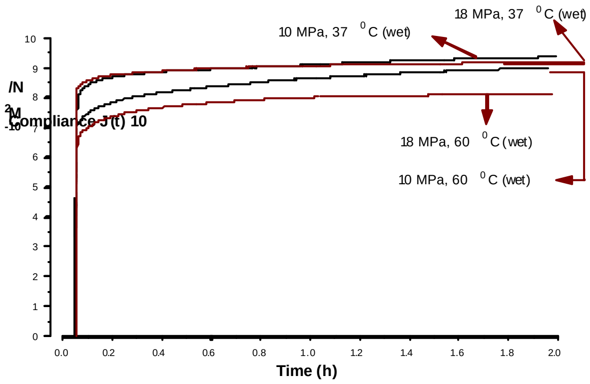


Fig. 6- The compliance behaviour of dentin at two temperatures (37, 60 °C) during 10 and 18 MPa compressive stresses (each curve represented the mean of compliance obtained from six dentin samples)

Discussion

Craig and Peyton mentioned that the length/diameter ratio of dentin specimens may appear to have some effect on the elastic modulus but it was independent of the length/diameter ratio in the range 1 to 2.5. They reported that for ratios between 1 and 0.5 the elastic modulus values were slightly lower and appeared to be caused by the following factors:

1-an actual decrease in the elastic modulus and

2- a lower slope of the stress-strain plot (lower modulus) obtained as a result of non-parallel ends of the specimens.[14]

Craig suggested using cylindrical specimens with a length approximately twice that of the diameter for obtaining better results because of the complicated force distributions in the ends of the cylinder in too short specimens. However, in our experiments, the length/diameter ratio was 1.8/3= 0.6. Because the tubules and their orientation have an important role in mechanical properties, an attempt was made to obtain all of the specimens from the same portion of the teeth. Figure 1 shows the specimen preparation from the coronal portion of the teeth. The handling of specimens, both in preparation and placement under the creep apparatus, was easy. Preparation of cylindrical paralleled-ended specimens with 3-mm diameter of dentin from non-coronal portions of tooth without the interference of pulp horns and pulp chamber seems difficult. The specimens were prepared from molar teeth, particularly third molars, which are more available than canines and incisors.[15]. All of the preparation of the cylindrical shape was done by high speed handpieces with fissure diamond burs, similar to clinical preparation.

The economy of usage teeth seems greater than with other sample preparations. Duncanson and Korostroff and Korostroff et al prepared the specimens from the roots of maxillary incisors and canines so as to obtain maximum specimen volume and uniform radial orientation of dentinal tubules by machining [16,17]

Stanford et al prepared cylindrical specimens from dentin slices by a milling machine. [7]

Trengrove et al produced dentin cylinders from the middle-third of the root.[4]

Then, the root canal in each specimen was enlarged to a diameter of 1.0 mm with a stainless steel drill. After examination *a total of only 68 specimens were accepted from the total 196 preparations due to cracks or irregularities,* in this previous work.

The ratio of stress to strain is termed the modulus (**E**), which is a function of time. The initial compressive modulus was obtained from the ratio of stress to initial strain at 20 seconds. This strain shows the elastic part of the overall creep graphs. In order to determine this modulus from a strain-time curve, the creep-strain at the elastic limit is read off from the curve and its ratio calculated to the compressive uniaxial stress. The initial creep values were compared with elastic modulus obtained from static experiments.

Elastic modulus is a term that describes the measure of elasticity of a material. It represents the stiffness of a material within the elastic range, which can be determined from a stress-strain curve, by calculating the ratio of stress to strain of the linear region of the curve. It can also be determined from the ratio of the elastic limit of a compressive curve and the applied constant compressive stress. It is calculated from the relation, **E** = s/e, and since e is dimensionless, **E** is expressed in GPa. The fundamental property of a material is its elastic qualities and the interatomic or intermolecular forces operating within the material are responsible for these elastic properties. It has been reported that the values of the elastic modulus are higher for stronger forces of attraction resulting in a more rigid material. However, the elastic property is generally independent of any heat treatment or mechanical treatment but is dependent, to a large extent, on the material's composition.

Dentin consists of a composite structure with microscopic hydroxyapatite crystals embedded in the matrix of collagen biopolymers. Dentin has been shown to exhibit visco-elastic as well as elastic properties.(16,17) Chemical and physical characteristics of dentin are responsible for its viscoelastic and elastic behaviour. Dorrington reported viscoelasticity as a major disturbing influence on any attempt to measure the equilibrium mechanical properties of a body tissue.(18) This behaviour is dominated by an instantaneous elastic strain and a retarded strain, with little viscous strain occurence. Data presented in this study are comparable in magnitude to other linearly viscoelastic materials.

The stresses applied in this study were 10 and 18 MPa which were below the proportional limits of the dental tissue. Data on creep of dentin including modulus of elasticity obtained in this study are comparable to the values by Watts et al(10) who reported a modulus of 13 GPa for dentin and a slight decrease in the range of 0-80°C. The value of the "static" modulus of elasticity for dentin (16.6 to 18.5 GPa) reported by Craig and Peyton(14) seems higher than our result. The values of modulus of elasticity reported by Waters at ambient temperature were 11-13 Gpa.(1) Viscoelastic behaviour of dentin tends to be influenced by the magnitude of the applied stress and temperatures. It was observed that increasing stress increased the value of the apparent modulus of elasticity.

There is a decrease in the magnitude of modulus of elasticity by increasing the temperature. The temperature-dependence of the modulus of dentin has been reported to have a statistically significant negative linear relationship.(10) A two-way analysis of variance showed significant difference between values of initial compressive modulus for the two variables of stress and temperature. Statistical analysis showed that changes in temperature and applied compressive stress influenced the maximum creep strain. Decrease in initial compressive modulus of dentin with increasing temperature paralleled a similar trend measured for compact bone by Bonfield and Li (19) and Bonfield and Tully.(20) Compressive modulus values deter-mined in this study were in agreement with the values of elastic modulus from compression tests over the temperature range of 30-60°C reported by Black, Peyton et al, Stanford et al and Craig and Peyton, (5,6,7,14) who reported values in the range of 11-17 GPa.

This study showed that creep-strain increased with increasing stress, which is in agreement with the *Boltzmann Superposition principle* indicating that the creep strain is directly proportional to the stress at any given time.

This study also showed that creep increased with increasing temperature which is in agreement with Ruyter and ∅ysæd,(21) Ruyter and Espevik, Odén et al(23) and Papadogianis et al(24) who reported increasing of creep with increasing temperature for denture base polymers and composites.

In this study, dentin undergoing viscoelastic deformation exhibited an irrecoverable strain referred to as a Permanent Set, $\mathbf{E_s}$. This result was in agreement with Korostoff et al[17] who proved that strains of 0.6% produce permanent changes in dentin which may be the result of dentinal tubules collapse brought about by stress concentrations at over stress levels of 50% of the compressive strength of dentin.

Creep compliance (J_t) was defined as the strain divided by the stress at a given time. The creep compliance curve therefore permits an estimate of the relative amount of elastic, anelastic and viscous behaviour of a material. J_0 indicates the flexibility and initial recovery after deformation, J_R the amount of delayed recovery that can be expected, and t/h the magnitude of permanent deformation to be expected. Thus, once a creep curve was obtained, the correspondding creep compliance was calculated. The strain associated with J_0 and J_R was completely recoverable after the load was removed. However, the strain associated with J_R was not recovered immediately but requires some finite time. The strain associated with t/h was not recovered and represents a permanent deformation.

If a single creep compliance curve is calculated from a family of creep curves determined at different stresses, the material is said to be linearly viscoelastic. The viscoelastic qualities can be described concisely by a single curve. Comparison between creep compliance curves with time-dependent creep curves presented in Figure 6 shows the curves were not changed by stresses, and the curves could be superimposed. However, difference in compliance are evident when comparing them at the two temperatures (37, 60°C) under a stress system e.g. 10 MPa. In this study, the strain was directly proportional to the stress at any given time but the creep compliance was independent of the stress. Perhaps, this is generally true for small stresses, and the principle is not exact for the large stresses encountered.

The compliance recovery curves of the dentin seem consistent with linear viscoelastic behaviour when the stresses changed from the 10 to 18 MPa. However, some non-linearity of behaviour was shown when the temperatures changed from 37 to 60°C for each stress (Fig. 6).[25] It should be noted that recovery was allowed for two hours, although complete recovery was not attained during this period. A longer recovery measurement-period may be recommendded in order to confirm a permanent set.

Conclusion

Dentin, a mineralized tissue similar to bone structurally and chemically, is seen to exhibit viscoelastic behaviour, characterised by an instantaneous elastic strain and a retarded strain, followed by a little viscous strain. Despite the complex structure of dentin at several levels, this work has shown that its mechanical behaviour is amenable using the principles of viscoelastic theory.

The results suggest that compressive strain >0.6% produced permanent changes in dentin attributed to stress concentrations of ~50% of the compressive stress of dentin. Temperature increases at the same compressive stress levels has resulted in creep and residual strain increasing with decrease in compressive modulus. The observed residual strain was as a result of the viscous flow, although the forces of compression applied were relatively small.

There was a decrease in the magnitude of modulus of elasticity by increasing the temperature. There was an increase trend in maximum strain with increasing the temperature or stress.

Decrease in initial compressive modulus of dentin with increasing temperature was found.

Dentin was found to exhibit a linear viscoelastic response under 'clinical' compressive stress levels, such as those applied to the specimens in this investigations, with a maximum strain ~ 1% a high recoverability and permanent set <0.3%. This observation tends to establish a performance standard for viscoelastic stability of restorative biomaterials in replacing human dentin.

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