Chapter A3
Dentin and Enamel

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A3.1 Introduction

A3.1.1 Structure of human dentition:

The permanent adult human dentition normally consists of 32 teeth, of which 16 are located in the mandible and 16 in the maxilla. There are 4 incisors, 2 canines, 4 premolars and 6 molars for the upper and lower dentition. The incisors are used for cutting food, the canines for tearing, the premolars for grasping, and the molars for grinding (i.e., masticating). There is a generic heterogeneous structure for these teeth, where enamel forms an exterior layer over the underlying dentin. From the cervix to the apex of the root, the exterior of the dentin is covered by cementum to which the periodontal ligament attaches the tooth to alveolar bone. Dental enamel is dense, highly mineralized, hard, and brittle. It contains prism-like structures that span from the enamel surface to the junction of enamel and dentin, the dentino-enamel junction (DEJ). The prisms are comprised of hydroxyapatite crystallites and contain very little organic matrix. These properties make dental enamel an excellent material for cutting and masticating food (i.e., processes that involve friction and wear). In contrast, dentin is not as hard as enamel, but it is tougher. Dentin is a heterogeneous material and can be thought of as a composite structure containing four major components: dentin matrix; dentinal tubules; mineral (i.e., carbonate containing hydroxyapatite); and, dentinal fluid. The dentinal tubules (~45 000 per mm^2) are formed during development of the dentin matrix and are distributed

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throughout the dentin matrix in a somewhat uniform manner. The dentin matrix mineralizes in an anisotropic fashion, where a highly mineralized tissue, peritubular dentin, surrounds the dentinal tubules. The mineralized tissue between the dentinal tubules and peritubular dentin is referred to as intertubular dentin. Histological examination has revealed that intertubular dentin is less mineralized than peritubular dentin. Furthermore, the matrix and mineral content of root dentin is different from coronal dentin. A good review of the structure of teeth can be found in Waters [1].

A3.2 Composition

Table A3.1 Basic Constituents of Human Dentin and Enamel*

	Enamel		Dentin	
	Weight %	Volume %	Weight %	Volume %
Mineral (density, 3000 kg m^{-3})	96	90	70	50
Organic (density, 1400 kg m^{-3})	1	2	20	30
Water (density, 1000 kg m^{-3})	3	8	10	20

* Adapted from [1–3].

Table A3.2 Major Elemental Composition of Surface and Bulk Dental Enamel

	Enamel Mean wt% (range or standard deviation, ±)	Dentin Mean wt% (range or standard deviation, ±)	Source, Comments
Ca	37.4 ± 1.0	–	[4]#
	37.1 ± 0.2 (26.7–47.9)	26.9 ± 0.2 (21.8–31.3)	[5]#
	36.3 ± 0.1 (27.7–42.0)	27.6 ± 0.1 (24.7–31.5)	[5]‡
P	17.8 ± 0.2	13.5 ± 0.1	[5]●, age >25yrs
	17.68 ± 0.2		[6]¤
Na	0.72 ± 0.008 (0.42–1.03)	0.72 ± 0.008 (0.26–0.87)	[5]#
	0.72 ± 0.008 (0.49–0.88)	0.64 ± 0.001 (0.55–0.75)	[5]‡
Cl	0.28 ± 0.01	0.05 ± 0.004	[5]#, age >25yrs
	0.32 ± 0.01	0.072 ± 0.022	[7]#
K	0.026 ± 0.001	0.02 ± 0.001	[5]‡, age <25yrs
Mg	0.39 ± 0.02 (0.13–0.77)	0.74 ± 0.02 (0.25–0.94)	[5]#
	0.39 ± 0.004 (0.24–0.48)	0.76 ± 0.004 (0.58–0.89)	[5]‡
CO_3	3.2 (2.4–4.2)	4.6 (4–5)	[2,3]†

Neutron activated gamma-ray spectrometric analysis.
‡ Atomic absorption spectrophotometry.
● Colorimetric assay.
† Average compiled from the literature.
* Neutron activated gamma-ray spectrometric analysis (Na, Cl, Al, Mn, Ca, and P), atomic absorption spectrophotometry (K, Mg, Zn, Cu, and Fe), or a fluoride-specific electrode (F).
¤ Atomic absorption spectrophotometry (Ca), and colorimetric method (P).

Table A3.3 Trace Elemental Composition of Surface and Bulk Dental Enamel

		Surface Enamel		Whole Enamel		
	At.#	Mean (range) μg/g	Median μg/g	Mean (range) μg/g	Median μg/g	Source, comments
S	16			281 (530–130)	270	[8]†,[9]‡
F	9	752 (1948–25)	666	293 (730–95)	200	[8]†,[9]‡
				123.8 ± 7.9		[10]◊
Zn	30	893 (5400–61)	576	199 (400–91)	190	[8]†,[9]‡
				276 ± 106		[4]#
				263.42 ± 14.8		[10]◊
Mg	12	745 (3600–115)	576	1,670 (3,000–470)	1,550	[8]†,[9]‡
AI	13	343 (2304–16)	202	12.5 (70–1.5)	5.6	[8]†,[9]‡
Sr	38	204 (7632–9)	36	81 (280–26)	56	[8]†,[9]‡
				93.5 ± 21.9		[4]#
				111.19 ± 9.86		[10]◊
Fe	26	138 (1404–18)	68	4.4 (21–0.8)	2.6	[8]†,[9]‡
				2.77		[7]*
Si	14	70 (504–1.3)	40			[8]†,[9]‡
Mn	25	59 (468–2.6)	33	0.28 (0.64–0.08)	0.26	[8]†,[9]‡
				0.54 ± 0.08		[4]#
				0.59 ± 0.04		[10]◊
Ag	47	32 (396–0.2)	2	0.35 (1.3–0.03)	0.16	[8]†,[9]‡
				0.56 ± 0.29		[10]◊
Pb	82	24 (79–1.2)	18	3.6 (6.5–1.3)	3.6	[8]†,[9]‡
Ni	28	23 (270–0.4)	9			[8]†,[9]‡
Ba	56	22 (432–0.8)	7	4.2 (13–0.8)	3.4	[8]†,[9]‡
Se	34	18 (72–2.9)	16	0.27 (0.5–0.12)	0.22	[8]†,[9]‡
Li	3	14 (58–0.3)	10	1.13 (3.4–0.23)	0.93	[8]†,[9]‡
Sb	51	8 (90–0)	3	0.13 (0.34–0.02)	0.11	[8]†,[9]‡
Ga	31	6 (32–0)	5			[8]†,[9]‡
Sn	50	9.3 (72–0.9)	5.8	0.21 (0.92–0.03)	0.14	[8]†,[9]‡
Ge	32	7.6 (39.6–0.5)	4.0			[8]†,[9]‡
B	5	5.3 (13.0–0.8)	3.6	5.0 (39–0.5)	2.4	[8]†,[9]‡
Cu	29			4.20 (81–0.1)	0.45	[8]†,[9]‡
				0.26 ± 0.11		[4]#
				1.38		[7]*
Br	35	3.1 (14.0–0.4)	4.1	1.12 (2.6–0.32)	0.93	[8]†,[9]‡
				4.6 ± 1.1		[4]#
Cd	48	2.7 (7.6–0.6)	1.8	0.51 (2.4–0.03)	0.22	[8]†,[9]‡
Y	39	1.8 (9.3–0)	0.9	0.007 (0.17–<0.01)	<0.01	[8]†,[9]‡
Ti	22	1.6 (24.5–0.1)	0.6	0.19 (4.4–<0.1)	<0.1	[8]†,[9]‡
V	23	1.4 (14.4–0.1)	0.5	0.017 (0.03–0.01)	0.02	[8]†,[9]‡
La	57	1.4 (7.2–0)	0.8			[8]†,[9]‡
Be	4	1.3 (6.1–0)	1.2			[8]†,[9]‡
Cr	24	1.1 (4.7–0.2)	0.7	3.2 (18–0.1)	1.5	[8]†,[9]‡

Table A3.3 (continued)

		Surface Enamel		Whole Enamel		
	At.#	Mean (range) µg/g	Median µg/g	Mean (range) µg/g	Median µg/g	Source, comments
				1.02 ± 0.51		[10]◊
Rb	37	0.6 (4.0–0.1)	0.4	0.39 (0.87–0.17)	0.32	[8]†,[9]‡
Zr	40	0.6 (1.9–0)	0.3	0.1 (0.57–<0.02)	O.Q7	[8]†,[9]‡
Ce	58	0.6 (6.1–0)	0	0.07 (1.9–0.02)	0.07	[8]†,[9]‡
W	74			0.24 ± 0.12		[8]†,[9]‡
Co	27	0.2 (2.7–0)	0.1			[8]†,[9]‡
				0.13 ± 0.13		[10]◊
Pr	59	0.2 (4.7–0)	0	0.027 (0.07–<0.01)	0.03	[8]†,[9]‡
Cs	55	0.1 (1.9–0)	0	0.04 (0.1–<0.02)	0.04	[8]†,[9]‡
Mo	42	0.1 (0.5–0.04)	0.04	7.2 (39–0.7)	6.3	[8]†,[9]‡
I	53	0.05 (4.7–0)	0.05	0.036 (0.07–0.01)	0.03	[8]†,[9]‡
Bi	83	0.001 (0.04–0)	0	0.006 (0.07–<0.02)	0.02	[8]†,[9]‡
Nd	60	0.045 (0.09–<0.02)	0.05			[8]†,[9]‡
Nb	41			0.28 (0.76–<0.1)	0.24	[8]†,[9]‡
Au	79			0.02 ± 0.01		[4]#

‡ Whole enamel from premolars of young patients (age<20 yrs), determined by spark source mass spectroscopy.
† Surface enamel (depth of analysis 42 ± 8.5 µm) from premolars of young patients (age<20yrs), determined by spark source mass spectroscopy.
# Bulk enamel from premolars of 14–16 yrs male and female patients, selected population of Stockholm Sweden, determined by neutron activated gamma-ray spectrometric analysis. Standard deviation, ±.
◊ Neutron activated gamma-ray spectrometric analysis.
* Neutron activated gamma-ray spectrometric analysis (Na, Cl, AI, Mn, Ca, and P), atomic absorption spectrophotometry (K, Mg, Zn, Cu, and Fe), or a fluoride-specific electrode (F).

Table A3.4 Significant Differences in Trace Element Composition of Whole Human Enamel for High and Low Caries Populationst†

	At.#	High Caries (Mean ± SE), µg/g	Low Caries (Mean ± SE), µg/g	Source
F	9	82.1 ± 7.99	125.7 ± 11.23	[11]
Sr	38	104.1 ± 9.14	184.0 ± 14.68	[11]
Mn	25	1.57 ± 0.24	0.87 ± 0.15	[12]
Zr	40	0.27 ± 0.1	0.16 ± 0.09	[11]
Cu	26	0.71 ± 0.2	0.17 ± 0.04	[12]

† Determined by spark source mass spectroscopy

Table A3.5 Ca/P Molar Ratio of Human Enamel and Dentin

Enamel Ca/P molar ratio	Dentin Ca/P molar ratio	Source, comments
1.58		[4]#
1.61	1.54	[5]†, ●, age >25 yrs
1.58	1.58	[5]*, ●, age >25 yrs
1.65		13]**
1.64		[6]¤
	1.61	[14]**

Neutron activated gamma-ray spectrometric analysis.
† Ca determined by neutron activated gamma-ray spectrometric analysis
* Ca determined by atomic absorption spectrophotometry
● P determined by colorimetic assay.
** Determined by energy dispersive X-ray analysis.
¤ Determined by atomic absorption spectrophotometry (Ca), and by the colorimetric method (P).

Table A3.6 Crystallite Size and Lattice Parameters of the Apatite in Human Enamel and Dentin*

	a-axis (nm)	c-axis (nm)	Width (nm)	Thickness (nm)	Source, Comments
Enamel					
	0.9445	0.6885			[2]#
	0.9440	0.6872			[15]†
	0.9441	0.6880	68.4 ± 3.4	26.3 ± 2.2	[6]†, ● ±S.D.
	0.9446	0.6886			[16]†
			68.3 ± 13.4	26.3 ± 2.19	[17]‡,● ± S.E.
Dentin					
	0.9434 ±	0.6868 ±	[18]‡		
	0.0007	0.0009	29.6 ± 3.7	3.2 ± 0.5	[19]●, intertubular dentin
			36.55 ± 1.45	10.33 ± 7.91	[20]●, mixed carious and sound dentin

* Asymmetric hexagonal crystal with the thickness of the crystal less than the width.
† X-ray diffraction method of determination.
● High resolution transmission electron microscopy.
Data from [2], average compiled from the literature.

Table A3.7 Elastic Moduli and Viscoelastic Properties of Human Dentin and Enamel

	Incisors	Canine	Pre-molars	Molars	Source, Comments
E: Dentin					
				11.0 (5.8)	[21]t,†,‡
	13 (4)	14 (6)	14 (0.7)	12 (2)	[22]Crown, c,†
	9.7 (2)	12 (3)	9.0 (2)	7.6 (3)	[22]Root, c,†
				10.16	[23]b,ll
				10.87	[23] b,dehyd., ll
				9.49	[23] b, re-hyd, ll
E: Enamel					
				84.3 (8.9)	[24]Cusp, c, ll
				77.9 (4.8)	[24]Side, c, ll
		48 (6)		46 (5)	[22]Cusp, c,‡
		33 (2)		32 (4)	[22]Axial (side), c, ^
				9.7 (3)	[22]Axial (side), c, ll
				12 (3)	[22]Occlusal, c, ll
E,(∞): Dentin					
				12	[25]c, constant strain, hydrated,^,‡
H_1(t): Dentin					
				0.38	[25] c, constant
				(0.136)	strain, hydrated,^,‡

E: modulus of elasticity (GPa); E_r (∞): relaxed modulus (GPa); H_1(t): distribution of relaxation times (GPa); c: compression; t: tension; b: three-point bending.
ll Applied load approximately parallel to either the long axis of the enamel rods or dentinal tubules.
^ Applied load approximately perpendicular to either the long axis of the enamel rods or dentinal tubules.
† Applied load with respect to either the long axis of the enamel rods or dentinal tubules was variable.
‡ Type of tooth unknown or various teeth used for measurement; data are tabulated under molar.
Note: standard deviations are given in parentheses.

Table A3.8 Mechanical Properties of Human Enamel

	Incisors	Canine	Pre-molars	Molars	Source, comments
Stress at				353 (83)	[24]Cusp, c, ll
Proportional				336 (61)	[24]Axial(side), c, ll
Limit (MPa)		194 (19)		224 (26)	[22]Cusp, c,†
		183 (12)		186.2 (17)	[22]Axial (side), c, ^
				70.3 (22)	[22]Axial (side), c, ll
				98.6 (26)	[22]Occlusal, c, ll
		91.0 (10)			[22]Incisal edge, c,†
Tensile Strength (MPa)				10 (2.6)	[26]†
Compressive				384 (92)	[24]Cusp, c, ll
Strength (MPa)				372 (56)	[24]Axial (side), c, ll
		288 (48)		261 (41)	[22]Cusp, c,†
		253(35)		239 (30)	[22]Axial (side), c, ^

(continued)

Table A3.8 (continued)

	Incisors	Canine	Pre-molars	Molars	Source, comments
				94.5 (32)	[22]Axial (side), c, ǁ
				127 (30)	[22]Occlusal, c, ǁ
		220 (13)			[22]Incisal edge, c,†

c: compression; hyd: hydrated; dehyd: dehydrated; re-hyd: re-hydrated.
ǁ Fracture or applied load approximately parallel to the long axis of the enamel rods.
^ Fracture or applied load approximately perpendicular to the long axis of the enamel rods.
† Applied load with respect to either the long axis of the enamel rods or dentinal tubules was variable.
‡ Type of tooth unknown or various teeth used for measurement; data are tabulated under molar.
Note: standard deviations are given in parentheses.

Table A3.9 Mechanical Properties of Human Dentin

	Incisors	Canine	Pre-molars	Molars	Comments
Stress at				167 (20.0)	[24]c
Proportional	124 (26)	140 (15)	146 (17)	148 (21)	[22]c
Limit (MPa)	86 (24)	112 (34)	110 (38)	108 (39)	[22]c
				110.5 (22.6)	[23]b, hyd., ǁ
				167.3 (37.5)	[23]b, dehyd, ǁ
				103.1 (16.8)	[23]b, re-hyd, ǁ
				158 (32)	[17]
				154 (23)	[17]
Tensile				52 (10)	[26]hyd, †,‡
Strength				37.3 (13.6)	[23]hyd, ǁ
(MPa)				34.5 (11.1)	[23]dehyd, ǁ
				37.3 (9.0)	[23]re-hyd, ǁ
				39.3 (7.4)	[21]hyd,†, ‡
Compressive				297 (24.8)	[24]Crown
Strength	232 (21)	276 (72)	248 (10)	305 (59)	[22] Crown
(MPa)	233 (66)	217 (26)	231 (38)	250 (60)	[22]Root
				295 (21)	[23]Crown,‡
				251 (30)	[23]Crown, ‡
Shear Strength				134 (4.5)	[27]Oil, Cervical
(MPa)					root, ^, ‡
Flexural				165.6 (36.1)	[23]hyd, ǁ
Strength				167.3 (37.5)	[23]dehyd, ǁ
(MPa)				162.5 (25.4)	[23]re-hyd, ǁ

hyd: hydrated; dehyd: dehydrated; re-hyd: re-hydrated
ǁ Applied load approximately parallel to the long axis of the dentinal tubules
* Applied load approximately perpendicular to the long axis of the dentinal tubules;
‡ Type of tooth unknown or various teeth used for measurement; data are tabulated under molar;
† Applied load with respect to either the long axis of the dentinal tubules was variable.
‡ 95% confidence intervals.
Note: standard deviations are given in parentheses.

Table A3.10 Toughness, Fracture Toughness, and Work of Fracture of Human Dentin and Enamel

	Incisors	Canine	Pre-molars	Molars	Source, comments
Fracture					
Toughness,					
Kc ($MNm^{-3/2}$)					
					[28]*
Enamel	0.97(0.09)	1.00(0.23)			Maxillary,
					cervical, †
	1.27(0.09)			0.7(0.08)	Mandibular,
					cervical, †
Toughness (MJm^{-3})					
Dentin				62.7 (6.2)†	[27] Root, shear,
					oil storage, ^, ‡
				2.4 (1.1)	[17]Tension,
					crown, hydr., ǁ
Work of Fracture					
(10^2 Jm^{-2}) Dentine			2.7 (1.6)		[29],^
			5.5 (1.7)		[29] ǁ
Enamel			1.9(0.56)		[29], ^
			0.13(.065)		[29] ǁ

ǁ Applied load approximately parallel to either the long axis of the enamel rods or dentinal tubules.

^ Applied load approximately perpendicular to either the long axis of the enamel rods or dentinal tubules.

† Applied load with respect to either the long axis of the enamel rods or dentinal tubules was variable.

‡ Type of tooth unknown or various teeth used for measurement; data are tabulated under molar.

* Microindentation method used. Load was 500 g with a Vickers' indenter.

Note: standard deviations are given in parentheses.

Table A3.11 Hardness of Fracture of Human Dentin and Enamel (see notes for units)

	Incisor	Pre-molar	Molar	Source, comments
Enamel	365 (35)			[30] >90% incisors,®, †
			393 (50)	[30]‡, molars and premolars,®, †
			385 (5.8)	[31]⨂ † ‡
		367 (17)		[32] ॥,⨂, incisors, premolars
		327 (34)		[32]^,⨂, incisors, premolars
Dentin				
			25–81.7	[33]Δ, ॥, [34][a]
			97.8	[33]a, calculated for zero tubule density
			44.5–80.9	[14]◊, ॥, [34][a]
			100	[14]a, calculated for zero tubule density
			75 (0.8)	[31]⨂,†,‡

[a] Inverse correlation between hardness and dentinal tubule density.
॥ Applied load approximately parallel to either the long axis of the enamel rods or dentinal tubules.
^ Applied load approximately perpendicular to either the long axis of the enamel rods or dentinal tubules.
† Applied load with respect to either the long axis of the enamel rods or dentinal tubules was variable.
‡ Type of tooth unknown or various teeth used for measurement; data are tabulated under molar.
* Microindentation method used. Load was 500 g with a Vickers' indenter.
® Knoop hardness test using 500 g load.
⨂ Knoop microhardness test using 50 g load.
Δ Knoop microhardness test using 100 g load.
◊ Micromdentation method used. Load was 50 g with a Vickers' indenter.

Table A3.12 Permeability[a] of Human Dentin

Periphery(μl cm^{-2} min^{-1})	Center (μl cm^{-2} min^{-1})	Source, comments
36.4 (13.1)‡	14.3 (7.0)†	[33], unerupted third molars,

[a] Fluid filtration rate.
‡ Sound human dentin, average of 4 samples, 4 readings per sample.
† Sound human dentin, average of 4 samples, 1 reading per sample.

Table A3.13 Wetability of Human Enamel

		Contact Angle, θ(deg)		
Liquid	Surface Tension, γLV (dynes/em)	In situ enamel	Ground enamel	Source Comments
Polar				
Water	72.4 [35]	25.4 [36]†		
	72.8	36		[37]
	72.6		40.0 (0.1)	[38]* n=330
Glycerol	63.7 [35]	44.7 [36]†		
	63.4	55		[37]
	63.4		45.6(0.2)	[38]* n=50
Formamide	58.5 [35]	28.0 [35]†		
	58.2	24		[36]
	58.2		37.6 (0.1)	[37]* n=50
Thiodiglycol	53.5 [34]	30.8 [36]†		
	54.0	43		[37]
	54.0		27.6 (0.2)	[38]* n=60
Non-polar				
Methylene iodide	51.7 [35]	48.6 [36]†		
	50.8	50		[37]
	50.8		38.1 (0.1)	[38] n=50
S-Tetrabromoethane	49.8 [35]	38.3 [36]†		
	47.5	40		[38]
1- Bromonaphthalene	44.6	34		[38]*, n=50
	44.6		16.1 (0.1)	
o-Dibromobenzene	42.0	22		[37]
Propylene carbonate	41.8 [35]	31.8 [36]†		
1-Methyl-naphthalene	38.7	20		[36]
Dicyclohexyl	32.7 [35]	12.2-spread		[37]
	33.0	7		[36]†
n-Hexadecane	27.6 [35]	spreading		[37]
	27.7	spreading		[36]†

* Plane ground enamel surfaces, measurements from 46 erupted and unerupted teeth, mixed location (molars, premolars, incisors). Parentheses: standard error

† *in situ* contact angle measurements on human enamel, average of mean values for 4 teeth (maxillary or mandibular incisors).

Table A3.14 Wetability of Human Dentin [38]

Liquid	Surface Tension, γLV (dynes/em)	Ground Dentin Contact Angle, θ (deg)	Comments
Polar			
Water	72.6	45.3 (0.2)	*, n=100
Glycerol	63.4	44.6 (0.1)	*, n=50
Formamide	58.2	37.6 (0.2)	*, n=50
Thiodiglycol	54.0	33.6 (0.3)	*, n=50
Non-polar			
Methylene iodide	50.8	36.7 (0.3)	*, n=50
1-bromo-naphthalene	49.8	16.8 (0.2)	*, n=50

* Plane ground dentin surfaces, measurements from 46 erupted and unerupted teeth, mixed location (molars, premolars, incisors). Parentheses: standard error.

Table A3.15 Critical Surface Tensions (γ_c) of Human Enamel and Dentin

	Critical Surface Tension, γ_c (dynes cm^{-1})	Source, Comments
Enamel Ground surface	46.1 (40.0 – 55.6)[a]	[38]*, calculated from polar and non-polar liquids
In situ enamel, γ_c^d	45.3 ± 70.2[b]	[39]Δ, calculated from polar liquids,
In situ enamel, γ_c^d	32.9 ± 4.7	[38]Δ, calculated from non-polar liquids
In situ enamel, γ_c^d	32	[37]†, calculated from non-polar liquids
Dentin	45.1 (40.7 – 51.1)[a]	[38]*, calculated from polar and non-polar liquids

[a] Range of values from different test liquids.
[b] Standard deviation.
* Plane ground dentin surfaces, measurements from 46 erupted and unerupted teeth, mixed location (molars, premolars, incisors). Parentheses: standard error.
Δ In situ measurements from 76 test subjects: 29 female and 47 male. Measurements made on teeth with intact pellicle (i.e., biofilm). γ_c^p only calculated from glycerol and thiodiglycol.
† Average of 4 teeth from 2 subjects. γ_c^d calculated from non-polar liquids.

A3.3 Final Comments

The quality of data presented can be inferred from the standard deviations or standard error associated with the mean values. In some cases the error can be attributed to either small sample populations or specimen preparation. Where possible, either the number of specimens used or the number of replications of a measurement was reported. The reader should use this information as a guideline of the quality of data. When data are reported for small sample populations, then these data were usually the only source for a given physical property. In review of the literature, specimen preparation appears to have had the most influence on the precision and accuracy of data. Sample collection and storage conditions (e.g., dehydration, cross-linking agents, exogenous contamination) need to be taken into consideration when utilizing the information tabulated. Additional sources of error are dependent on the analytical technique or test method used to make the measurement. It is more difficult to discern the influence of the instrumentation on the reliability of the measurements. However, confidence of the accuracy was judged based on the use of adequate control samples with known physical properties (e.g., correction of mechanical data). In light of these comments, data in the literature were deemed most accurate and appropriate for this handbook when the following conditions were met: the sample population was large; non-destructive specimen preparation and storage conditions were used; and, multiple replications of measurements on a single sample were performed.

There are significant omissions in the data available in the literature. Most notable, is the lack of quantitative analysis of the organic phase of dentin and enamel, and determination of the viscoelastic properties of dentin. The lack of data is attributed to the technical difficulty required to make such measurements and the heterogeneous nature of the dentin, which imparts large variations in these data depending on anatomical location. Other significance absences are the lack of electrical and thermal properties. Finally, vacancies in the tables provided demonstrate omissions in available data.

Additional Reading

Carter, J.M., Sorensen, S.E., Johnson, R.R., Teitelbaum, R.L. and Levine, M.S. (1983) Punch Shear Testing of Extracted Vital and Endodontically Treated Teeth. *J. Biomechanics* **16(10)**, 841–848.

Utilized a miniature punch shear apparatus to determine shear strength and toughness perpendicular to the direction of dentinal tubules. Dentin harvested from the cemento-enamel junction to one-third the distance to the root apex. Strengths: novel measurements, precise measurements, defined specimen location, defined orientation of testing. Limitations: tooth type not defined for ‘constrained’ tests, teeth stored in mineral oil prior to testing.

Driessens, F.C.M., and Verbeeck, R.M.H. (1990a) The Mineral in Tooth Enamel and Dental Carries. In *Biominerals*, F.C.M and Verbeeck, R.M.H. (eds), CRC Press, Boca Raton, Florida, pp. 105–161.

Driessens, F.C.M., and Verbeeck, R.M.H. (1990b) Dentin, Its Mineral and Caries, In *Biominerals*, F.C.M and Verbeeck, R.M.H. (eds), CRC Press, Boca Raton, Florida, pp. 163–178.

An authoritative text on biominerals with an excellent review of the properties of enamel and dentin. An excellent supplement to this handbook.

Glantz, P-O. (1969) On Wetability and Adhesiveness. *Odontologisk Revy*, **20 supp. 17**, 1–132.

Comprehensive assessment of the wetability of human enamel and dentin. Strengths include using multiple probe liquids on numerous teeth.

Korostoff, E., Pollack, S.R., and Duncanson, M.G. (1975) Viscoelastic Properties of Human Dentin. *J. Biomedical Materials Res.*, **9**, 661–674.

Measured some viscoelastic properties of human radicular dentin under constant strain. Linear viscoelastic theory applied. Strengths: unique examination of viscoelastic properties, defined orientation of dentinal tubules, storage conditions and testing environment well controlled. Limitations: large scatter in $H_1(t)$, mixed data for different teeth.

Marshall, G.W. (1993) Dentin: Microstructure and Characterization. *Quintessence International*, **24(9)**, 606–616.

A Review of the microstructure and characterization of dentin.

Waters, N.E. (1980) Some Mechanical and Physical Properties of Teeth. *Symposia of the Society for Experimental Biology*, **34**, 99–135.

Concise review of mechanical and physical properties of teeth. Good paper for anatomy of enamel and dentin.

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