NATIONAL BUREAU OF STANDARDS REPORT

6406

Progress Report

on

COMPRESSIVE PROPERTIES OF HARD TOOTH TISSUES
AND
SOME RESTORATIVE MATERIALS

by

John W. Stanford
Keith V. Weigel
George C. Paffenbarger
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U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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Abstract

An improved method for preparing cylinders of enamel and dentin has been developed. The method entails the use of a jeweler's lathe and a hydraulic handpiece. In addition to the hard tooth tissues, cylinderical specimens -- approximating the size of the samples of tooth structure -- of silicate cement, zinc phosphate cement, amalgam alloy, inlay casting gold alloys, plastic teeth and direct filling resin have been tested. The physical properties in compression for enamel range from 1.4×10^6 to 9.1×10^6 psi for modulus of elasticity; from 10,200 to 32,500 psi for proportional limit and from 13,700 to 42,300 psi for compressive strength depending upon location; that is, cusp, side or occlusal surface, type of tooth and orientation of structure. Dentin ranged from 1.1×10^6 to 2.4×10^6 psi for modulus of elasticity, from 12,500 to 24,400 psi for proportional limit and from 30,000 to 42,300 psi for compressive strength. The values for these properties of the restorative materials ranged from 0.27×10^6 to 11.8×10^6 psi, from 6,400 to 33,700 psi and from 9,700 to 57,800 psi, respectively.

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1. INTRODUCTION

The physical properties in compression of hard tooth tissues and of some restorative materials have been determined. The methods for preparing and testing very small cylinders were more precise than those previously reported.[1] The properties determined were modulus of elasticity, proportional limit and compressive strength. It was thought that the knowledge of these properties might be of assistance in designing cavity preparation, in evaluating dental filling materials, and in demonstrating possible physical changes in teeth with age, in pulp disease and death, and in different environments of development.

A review of previous determinations of physical properties of hard tooth tissues was presented in 1958.[1] At about the time of that report data were published by Craig and Peyton[2] on the elastic and mechanical properties of human dentin giving values of 2.4×10^6 to 2.7×10^6 psi, 24,200 psi and 43,100 psi for modulus of elasticity, proportional limit and compressive strength, respectively. These values agree within experimental limits with those of Stanford and others[1] in 1958.

2. PREPARATION OF SPECIMENS

Cylindrical specimens were prepared of enamel and dentin from different areas in the same teeth, different orientations of the structure, deciduous teeth, pulpless teeth, teeth of different ages, and teeth from an endemic area of fluoride.

The teeth from which the specimens were to be prepared were sectioned into blocks of tissue which were subsequently mounted in small collets in the jeweler's lathe shown in Figure 1. Diamond instruments mounted in a hydraulic handpiece (Figure 2A) were utilized as the cutting tools. A fine spray of water (Figure 2B) was provided for lubrication and cooling during the cutting operation. The combined free running speed of rotation of the diamond instrument and block of tooth structure (Figure 2C) was approximately 55,000 rpm. Light cuts (about 0.005 in. depth of cut) were made across the end of the block in order to true that end so that it would be perpendicular to the sides of the finished cylinder. Part of the block was then ground to a cylindrical shape. At this point the specimen was removed from the collet and turned end for end so that the excess tissue could be removed and the ends of the specimen made plane and parallel. The specimens were placed in distilled water until tested. It should be pointed out that due to the extreme brittleness of enamel, it is very difficult to prepare perfect cylinders even with the refined method of preparation. The data which appear later in this report were determined on specimens of enamel which showed no visible chipping or fractures under approximately thirty times magnification. The number of specimens accepted and tested was less than fifty percent of those prepared.

The cylindrical specimens of restorative materials, approximating the sizes of the samples of tooth structure, were fabricated in various ways. Those of three brands of silicate cement and the direct resin filling material were prepared by the method for compressive strength tests outlined in American Dental Association Specification No. 9 for dental silicate cement.[3] Specimens of three brands of zinc phosphate cement were prepared by the method outlined in American Dental Association Specification No. 8 for dental zinc phosphate cement.[4] The plastic teeth were sectioned into rectangular blocks which were then reduced to cylindrical specimens on the lathe. The three dental amalgam alloys were mixed and packed following the respective manufacturer's directions as closely as conditions permitted. The specimens of the hard, medium and soft inlay casting gold alloys were prepared from cast rods. The rods were cut into appropriate lengths and then reduced in dimensions on the lathe. With the exceptions of the inlay casting gold alloys and the plastic teeth, all of the restorative materials were tested, for their compressive properties, from one to two weeks after preparation.

3. TEST PROCEDURES

In addition to refining the method for preparing cylinders of hard tooth tissues, the testing equipment previously described was replaced by an Instron Testing Machine, a more sensitive loading device (Figure 3). A close-up of the rigid platen arrangement is shown in Figure 4. The application of load below the proportional limit was at speeds of 0.001 to 0.002 in./min. As previously reported in measuring the strain, the small size of the specimen (Figure 4A) made it necessary to fasten the Tuckerman Strain Gauges (Figure 4B) to the platens (Figure 4C). The strain measurements thus included errors due to deformation in those portions of the steel platens within the gauge length and due to foundation or end effects. The elastic deformation in the platens can be corrected for by the following equation, the derivation of which can be found in the previous report[1]:

$$\Delta = Z - \frac{P}{E_p}\left[\left(\frac{L_g - L_s}{A_p}\right) + \frac{2}{d_s}\right]$$

where:

Δ = corrected deformation

Z = observed deformation

P = load

L_g = gauge length of strain gauge

L_s = length of specimen

E_p = modulus of elasticity of the steel platen

A_p = cross sectional area of platen

d_s = diameter of specimen

Thus, the corrected strain, ε, = $\frac{\Delta}{L_s}$, and the modulus of elasticity of the specimen is given by the following equation:

$$E_s = \frac{P}{A_s \varepsilon}$$

In order to verify experimentally the accuracy of the testing equipment and correction procedure, cylinders approximating the size of tooth tissue specimens of a magnesium alloy, AZ31A; an aluminum alloy, 2024-T4; and lucite were tested in compression and the results corrected as outlined above. Moduli of elasticity were also determined in tension on rods of these three materials. The values for observed moduli in compression, corrected moduli in compression, observed moduli in tension and accepted moduli are given in Table 1.

Examination of Table 1 shows that the corrected values of moduli in compression agree within experimental limits with the accepted values. In the previous report[1] the corrected values for moduli in compression did not agree with the observed values in tension or the accepted values. This was attributed to gap effect or apparent shortening due to imperfect fit of ends of specimens with the platens, and other experimental errors.

Parallelism of the ends of the specimens was randomly checked by an electronic gauge system. The maximum degree of nonparallelism of the ends was 0.0002 inch. Therefore, it is believed that the refined methods of preparing and testing the extremely small specimens has largely eliminated the gross differences in corrected and accepted values for moduli previously obtained.

4. DISCUSSION OF RESULTS

The results for the properties of the hard tooth tissues appear in Tables 2 through 8. The data for dentin taken from the crownal portion of molars, bicuspids, cuspids and incisors (Table 2) show that, in general no significant differences in modulus of elasticity, proportional limit and compressive strength can be attributed to a particular type of tooth. The averages of results obtained appear to indicate that root dentin has a lower modulus (1.4×10^6 psi) than does crownal dentin (1.9×10^6 psi). Also root dentin, in general, exhibits a lower proportional limit and compressive strength than crownal dentin. However, when the ranges of values determined are examined, the differences cited may not be significant.

Enamel (Table 3) taken from the cusp of cuspids (Figure 5A) exhibited higher modulus of elasticity, proportional limit and compressive strength than enamel from the incisal edge (Figure 5B). The values for the properties determined on specimens of enamel from the labial side (Figure 5C) fall in between. There appeared to be an increase in stiffness (modulus) when testing severely mottled enamel from the cusp or labial side of cuspids from patients living in an endemic area of fluoride. The results for enamel taken from the incisal edge showed no difference in modulus when the environment of development is examined. The data appear to warrant further investigation in consideration of this factor.

In addition, specimens of enamel were taken from molars (Table 4). The data show that enamel from molars (Figure 6C, cusp and Figure 6D, side) exhibits about the same properties as does that from cuspids. The low modulus, proportional limit and compressive strength for enamel taken from transverse sections (Figure 6F), that is, sections parallel to the occlusal plane, of the teeth appear to agree well with those of occlusal enamel taken from longitudinal sections (Figure 6E, sections perpendicular to the dentino-enamel junction). This would confirm the previous observations[1] if it is assumed that the general direction of the enamel rods in specimens taken from these two areas would be lengthwise and if the primary failure were in the bonding material.

Dentin was also examined from the standpoint of environment of development. The results (Table 5), as might be expected, show no significant differences in the three physical properties determined.

In order to determine if possible the effect of the death of the pulp on the physical properties of hard tooth tissues, three pairs of corresponding vital and pulpless incisors (condition cited was at time of extraction) were utilized. The patients from which these teeth were extracted were thirty years of age or younger. The times of death of the pulps were not available. The crownal portions of the pulpless teeth were carious or largely artifically restored so that only the root portion could be used for comparison with the roots of vital incisors. The data (Table 6) show no significant differences when the results for the three physical properties are compared. It is possible that the time between death of the pulp and extraction may have been too short for sufficient physical changes to have taken place which would be revealed by these tests.

The physical properties of enamel and dentin taken from three deciduous molars were also determined. The data (Table 7) show that enamel specimens taken from the cusps exhibit higher stiffness, proportional limit and compressive strength than those taken from the buccal side. The values for the three properties determined on deciduous enamel agree very well, as do the values for deciduous dentin, with values for these two tissues from permanent teeth (Tables 2 and 3, respectively).

No attempt had been made to determine tubule direction in the specimens of crownal dentin as there did not appear to be any significant differences in values determined for the various types of teeth (Table 2). However, specimens were taken from sections prepared longitudinally; that is, from the occlusal surface through the enamel into the crownal dentin to the pulp chamber of a molar (Figure 6A). In addition, specimens were taken from sections prepared transversally; that is, in the occlusal plane of another molar (Figure 6B). Both teeth were from the same patient. The data (Table 8) do not show significant differences in the values for the three properties; thus, the original orientations of the dentin in the teeth do not appear to influence the physical properties. This substantiates the conclusion reached by Craig and Peyton.[2]

The compressive properties of some restorative materials are shown in Table 9. The materials are arranged in increasing order of stiffness (modulus of elasticity). The stiffness and compressive strength of enamel and dentin are higher than those of the restorative materials tested, with the exception of amalgam and both the medium and hard inlay casting gold alloys. No true compressive strengths of the inlay casting gold alloys could be determined as the specimens flattened into plates from plastic flow with constantly changing surface contact of the specimens with the platens. While the stiffness of the silicate cement was of the same order as dentin, its proportional limit and compressive strength were lower.

Stress-strain diagrams which were determined experimentally for enamel, dentin and the restorative materials appear in Figure 7. The differences in stiffness of the tissues and restorative materials can easily be seen when one compares the slopes of the straight line portions of the stress-strain curves. The steeper the slope the stiffer the tissue or material. A degree of measure of brittleness can also be ascertained from these curves. When the stress-strain curve deviates from the straight line relationship; that is; when the increment of strain produced for equal stresses applied are not constant, then the proportional limit of the material has been reached. Materials such as amalgam (Figure 7F), inlay casting gold alloys (Figure 7A, B, D) direct resin filling material (Figure 7I), zinc phosphate cement (Figure 7H), and human dentin (Figure 7G) exhibit greater plastic flow than silicate cement (Figure 7E) and enamel (Figure 7C) specimens of which fracture soon after reaching the proportional limit, showing a high degree of brittleness. (The extreme plastic flow of the inlay casting gold alloys could not be plotted due to the constantly changing cross-sectional area making the calculations of stress applied impossible.)

5. SUMMARY AND CONCLUSIONS

1. Improved methods of preparing and testing specimens of hard tooth tissues have been developed.

2. The values for the three physical properties of dentin do not appear to be affected by the type of tooth or the original orientation of the dentin as to tubule direction. On the average root dentin appears to have lower values for physical properties than does crownal dentin. However, the ranges of values for individual specimens of root and crownal dentin overlap.

3. The properties of enamel appear to depend on the orientation and original location, of the samples tested, in the tooth. Enamel is stiffer (higher modulus of elasticity) than dentin and exhibits, in some locations (cusp) a compressive strength equal to or similar to that

of dentin. The present data do not warrant any definite conclusion as to the apparent increase in stiffness of enamel when taken from patients' teeth developed in an endemic area of fluoride over that from teeth where no fluoride was present during development.

4. No significant differences were determined in the compressive properties of root dentin from vital and pulpless incisors.

5. The compressive properties of deciduous enamel and dentin are similar to those of the permanent tissues.

6. A comparison of the compressive properties of the restorative materials tested and the hard tooth tissues shows that the stiffness and compressive strength of enamel and dentin are higher than those of the restorative materials tested with the exception of amalgam and both the medium and hard inlay casting gold alloys.

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TABLE 1
Calibration Data for Determination
of
Modulus of Elasticity

Material	Average Dimensions of Specimens		Observed E Compression	Corrected E Compression	Observed E Tension	Accepted * E
	Length	Diameter				
	in.	in.	$x10^6$psi	$x10^6$psi	$x10^6$psi	$x10^6$psi
Lucite	0.130	0.061	0.47	0.48	0.45	——
Magnesium alloy, AZ31A	0.131	0.060	5.1	6.5	6.5	6.5
Aluminum alloy, 2024-T4	0.075	0.040	7.9	10.8	10.5	10.6

*Source: Metals handbook, The American Society for Metals, 1948.

TABLE 2
Compressive Properties of Dentin

Type of Tooth	Location of Specimens	No. of Speci- mens	Average Dimensions of Specimens		Property Determined			
					Modulus of Elasticity		Proportional Limit	Compressive Strength
			Length	Diameter	(a) observed	(b) corrected*		
			in.	in.	$\times 10^6$psi	$\times 10^6$psi	psi	psi
Molars	Crown	37	0.100	0.050	1.6±0.2	1.7±0.2	21,500±2,100	44,200±7,000
	Root	21	0.057	0.037	1.0±0.3	1.1±0.3	15,600±4,600	36,300±7,000
Bi- cuspids	Crown	9	0.112	0.054	1.8±0.1	2.0±0.1	21,200±2,100	36,000±1,100
	Root	22	0.061	0.041	1.2±0.2	1.3±0.2	16,000±6,500	33,500±4,700
Cuspids	Crown	10	0.075	0.039	1.8±0.6	2.0±0.6	20,300±1,700	40,100±8,900
	Root	18	0.074	0.040	1.6±0.3	1.7±0.3	16,200±4,500	31,500±3,200
In- cisors	Crown	9	0.098	0.060	1.7±0.5	1.9±0.5	18,000±2,700	33,700±2,600
	Root	12	0.060	0.036	1.3±0.2	1.4±0.2	12,500±3,200	33,800±7,800

*Modulus of elasticity corrected for elastic shortening of the platens and deformation of the platen surfaces.

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TABLE 3

Compressive Properties of Enamel
(Cuspids)
Environment of Development

Location	Environment	No. of Specimens	Average Dimensions of Specimens: Length	Average Dimensions of Specimens: Diameter	Property Determined: Modulus of Elasticity (a) observed	Modulus of Elasticity (b) corrected*	Proportional Limit	Compressive Strength
			in.	in.	$x10^6$psi	$x10^6$psi	psi	psi
Cusp	No Fluoride	7	0.045	0.036	5.2±0.5	6.9±0.6	28,200±2,200	41,800±5,800
	Endemic Fluoride	5	0.041	0.036	7.0±1.1	9.1±1.4	23,800±1,200	35,400±1,000
Labial Side	No Fluoride	6	0.037	0.028	3.7±0.2	4.8±0.2	26,600±6,000	36,700±4,200
	Endemic Fluoride	5	0.040	0.032	4.6±0.2	6.0±0.2	22,800±2,300	33,200±5,100
Incisal Edge	No Fluoride	4	0.033	0.032	2.2±0.5	2.9±0.6	13,200±1,000	31,900±1,200
	Endemic Fluoride	3	0.036	0.034	2.2±0.6	2.9±0.8	15,000±1,600	37,300±3,500

*Modulus of elasticity corrected for elastic shortening of the platens and deformation of the platen surfaces.

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TABLE 4
Compressive Properties of Enamel
(Location and Orientation)

Location	Orientation	No. of Specimens	Average Dimensions of Specimens: Length	Average Dimensions of Specimens: Diameter	Property Determined: Modulus of Elasticity (a) observed	Property Determined: Modulus of Elasticity (b) corrected*	Proportional Limit	Compressive Strength
			in.	in.	$x10^6$psi	$x10^6$psi	psi	psi
Cusp	Longitudinal	19	0.061	0.039	5.0±0.5	6.7±0.6	32,500±3,300	37,800±4,300
Side	Longitudinal	11	0.058	0.038	3.7±0.2	4.7±0.3	27,000±1,800	34,600±2,200
	Transverse	16	0.041	0.033	1.3±0.2	1.4±0.3	10,200±2,300	13,700±3,600
Occlusal Surface	Longitudinal	6	0.043	0.031	1.6±0.2	1.8±0.3	14,300±2,100	18,400±3,200

*Modulus of elasticity corrected for elastic shortening of the platens and deformation of the platen surfaces.

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TABLE 5
Compressive Properties of Dentin
Environment of Development

Environment	Number of Specimens	Average Dimensions of Specimens		Property Determined			
		Length	Diameter	Modulus of Elasticity (a) observed	Modulus of Elasticity (b) corrected*	Proportional Limit	Compressive Strength
		in.	in.	$x10^6$psi	$x10^6$psi	psi	psi
No Fluoride	15	0.075	0.039	1.8±0.3	1.9±0.3	18,800±2,500	38,300±7,500
Endemic Fluoride	8	0.063	0.040	1.6±0.2	1.7±0.2	20,000±1,000	35,900±6,500

*Modulus of elasticity corrected for elastic shortening of the platens and deformation of the platen surfaces.

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TABLE 6

Compressive Properties of Vital and Pulpless Incisors
(Root Dentin)

Incisor	Number of Specimens	Average Dimensions of Specimens		Property Determined			
				Modulus of Elasticity		Proportional Limit	Compressive Strength
		Length	Diameter	(a) observed	(b) corrected*		
		in.	in.	$x10^6$psi	$x10^6$psi	psi	psi
Vital	8	0.079	0.039	1.4±0.5	1.5±0.5	18,100±1,500	30,000±3,900
Pulpless	6	0.071	0.038	1.5±0.2	1.6±0.2	19,900±1,900	32,600±3,700

*Modulus of elasticity corrected for elastic shortening of the platens and deformation of the platen surfaces.

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TABLE 7
Compressive Properties of Enamel and Dentin
(Deciduous Molars)

Tissue	Number of Specimens	Average Dimensions of Specimens		Property Determined			
				Modulus of Elasticity		Proportional Limit	Compressive Strength
		Length	Diameter	(a) observed	(b) corrected*		
		in.	in.	$x10^6$psi	$x10^6$psi	psi	psi
Enamel							
Cusp	3	0.027	0.028	5.9±0.8	7.7±1.1	28,500± 500	42,300±8,000
Buccal Side	3	0.033	0.031	2.6±0.7	3.4±0.9	19,600±4,600	22,600±4,300
Dentin	5	0.076	0.039	1.7±0.2	1.9±0.2	22,900±5,700	42,300±6,300

*Modulus of elasticity corrected for elastic shortening of the platens and deformation of the platen surfaces.

TABLE 8

Compressive Properties of Dentin
(Orientation of Specimens)

Teeth Sectioned	Number of Specimens	Average Dimensions of Specimens		Property Determined			
				Modulus of Elasticity		Proportional Limit	Compressive Strength
		Length	Diameter	(a) observed	(b) corrected*		
		in.	in.	$x10^6$psi	$x10^6$psi	psi	psi
Trans- verse	5	0.084	0.041	2.0±0.2	2.4±0.3	24,400±3,400	36,400±2,300
Longi- tudinal	9	0.060	0.036	1.7±0.4	1.9±0.5	18,000±2,700	33,700±2,600

*Modulus of elasticity corrected for elastic shortening of the platens and deformation of the platen surfaces.

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TABLE 9

Compressive Properties of Some Restorative Materials

Material	No. of Speci-mens	Average Dimensions of Specimens		Property Determined			
				Modulus of Elasticity		Proportional Limit	Compressive Strength
		Length	Diameter	(a) observed	(b) corrected*		
		in.	in.	$x10^6$psi	$x10^6$psi	psi	psi
Direct Filling Resin	10	0.214	0.122	0.27±0.02	0.27±0.02	6,400± 400	11,000± 300
Plastic Teeth	10	0.120	0.058	0.36±0.02	0.36±0.02	7,500± 800	9,700± 200
Zinc Phosphate Cement	15	0.225	0.121	1.2 ±0.2	1.3 ±0.2	8,600± 500	12,000± 1,000
Amalgam	30	0.073	0.057	1.8 ±0.3	2.0 ±0.4	30,000±4,700	57,800±3,500
Silicate Cement	15	0.202	0.121	2.0 ±0.4	2.4 ±0.5	16,400±2,900	23,000±5,000
Inlay Golds							
Soft	5	0.124	0.080	5.1 ±0.2	6.5 ±0.3	9,600± 800	-----
Medium	5	0.141	0.071	8.3 ±0.4	11.3 ±0.7	24,100±1,200	-----
Hard	5	0.161	0.080	8.6 ±0.1	11.8 ±0.5	33,700±2,100	-----

*Modulus of elasticity corrected for elastic shortening of the platens and deformation of the platen surfaces.

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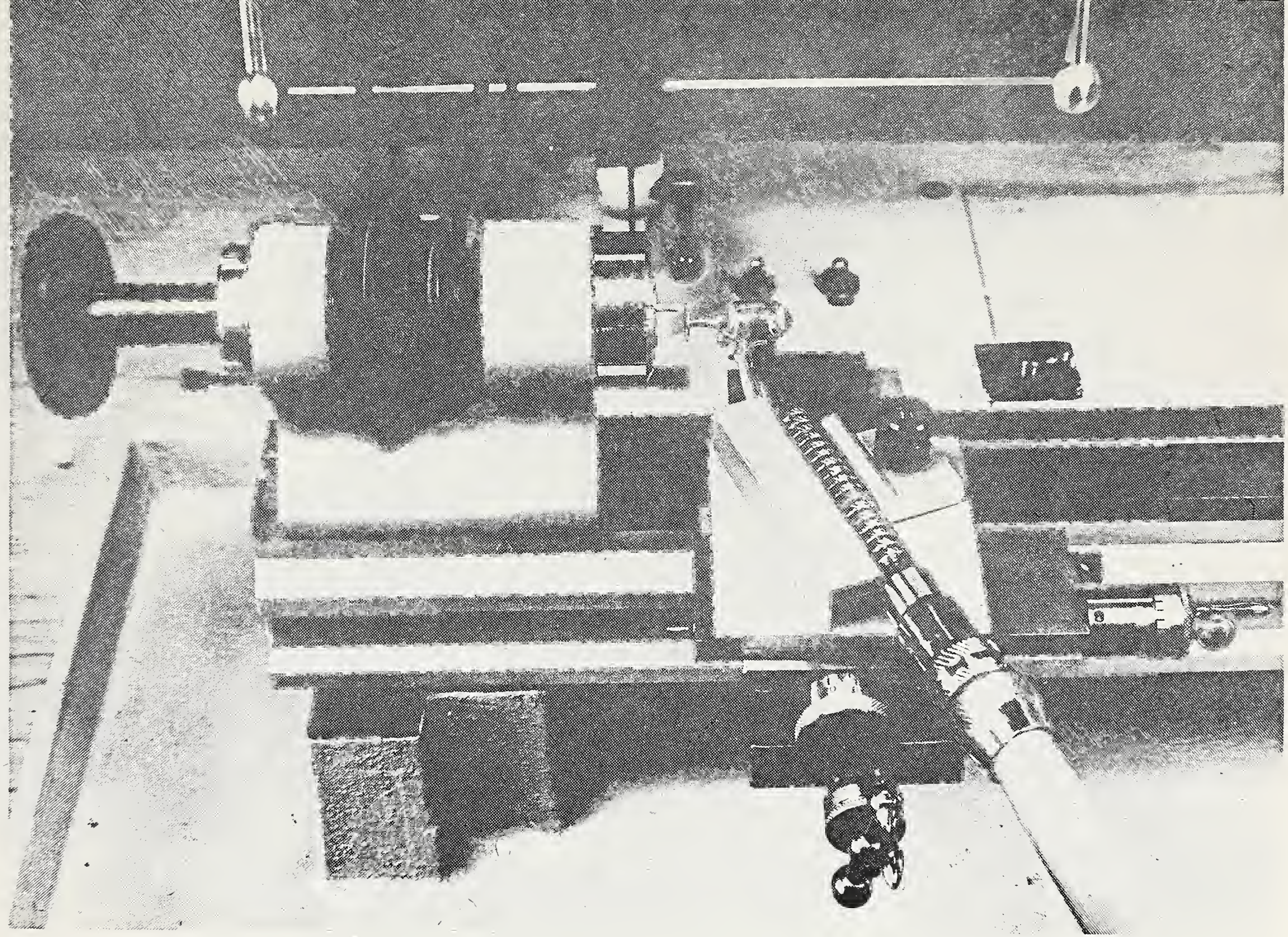

FIGURE 1

Jeweler's lathe and hydraulic handpiece

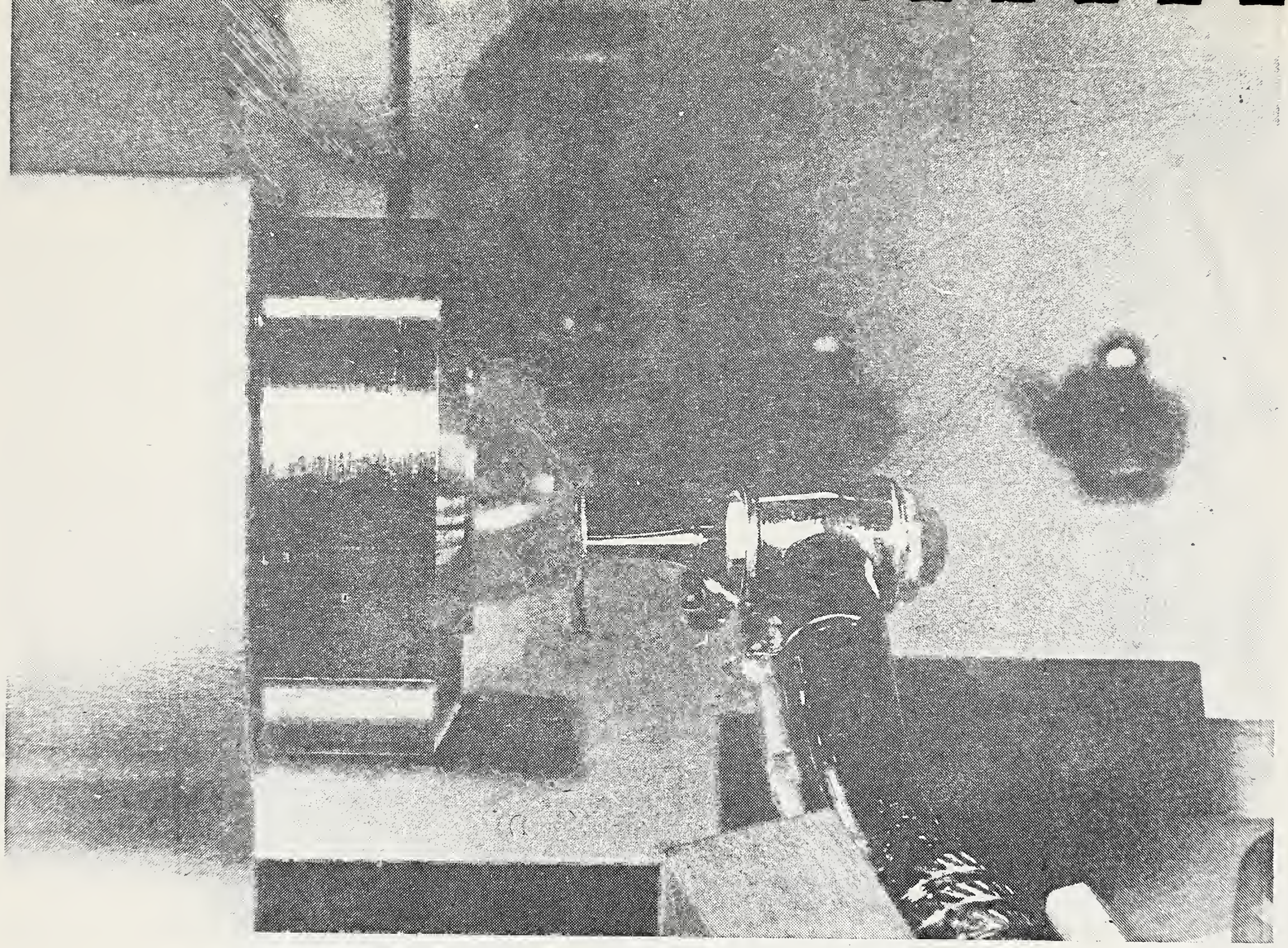

FIGURE 2
Close-up of cutting area

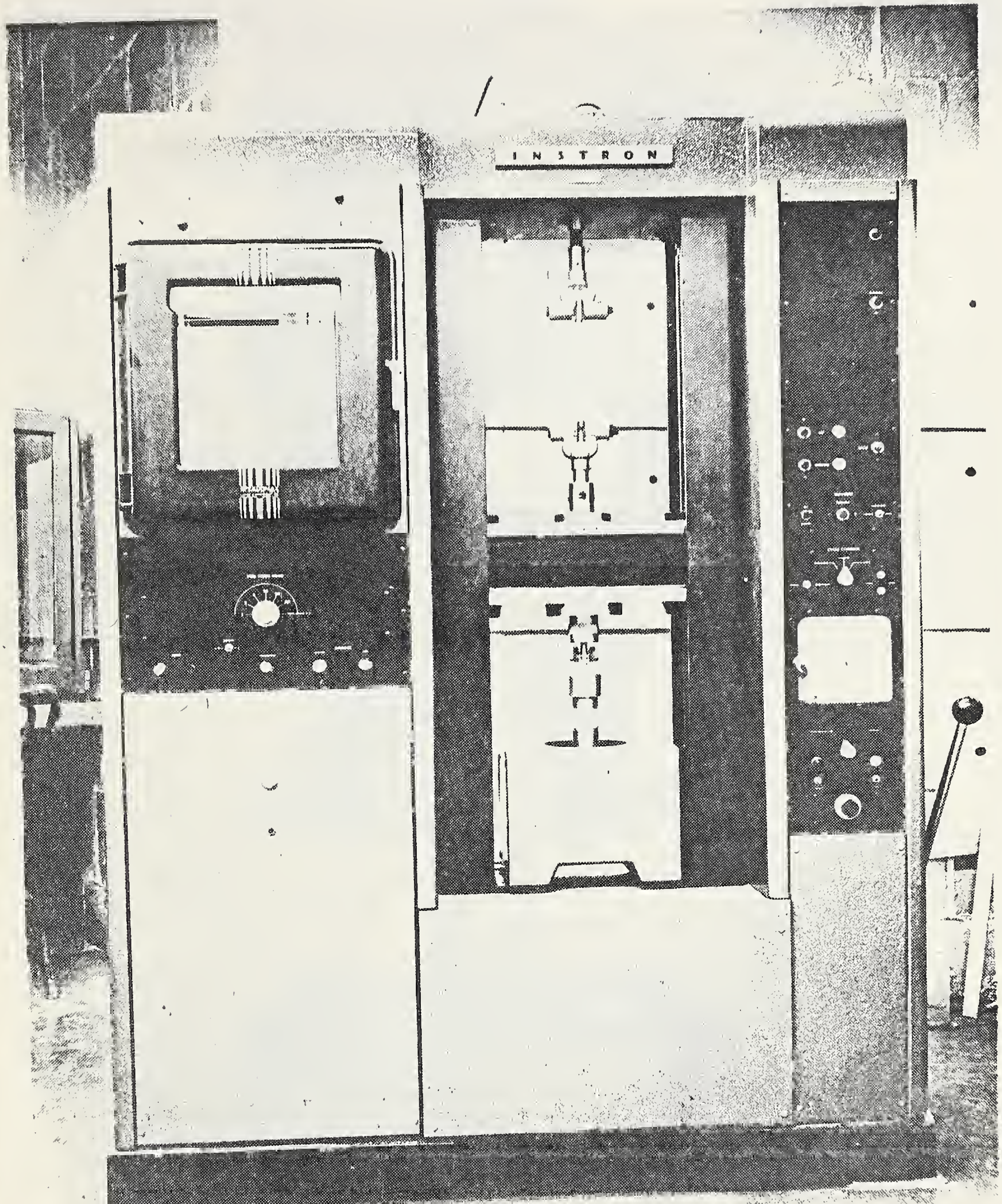

FIGURE 3

Instron testing machine

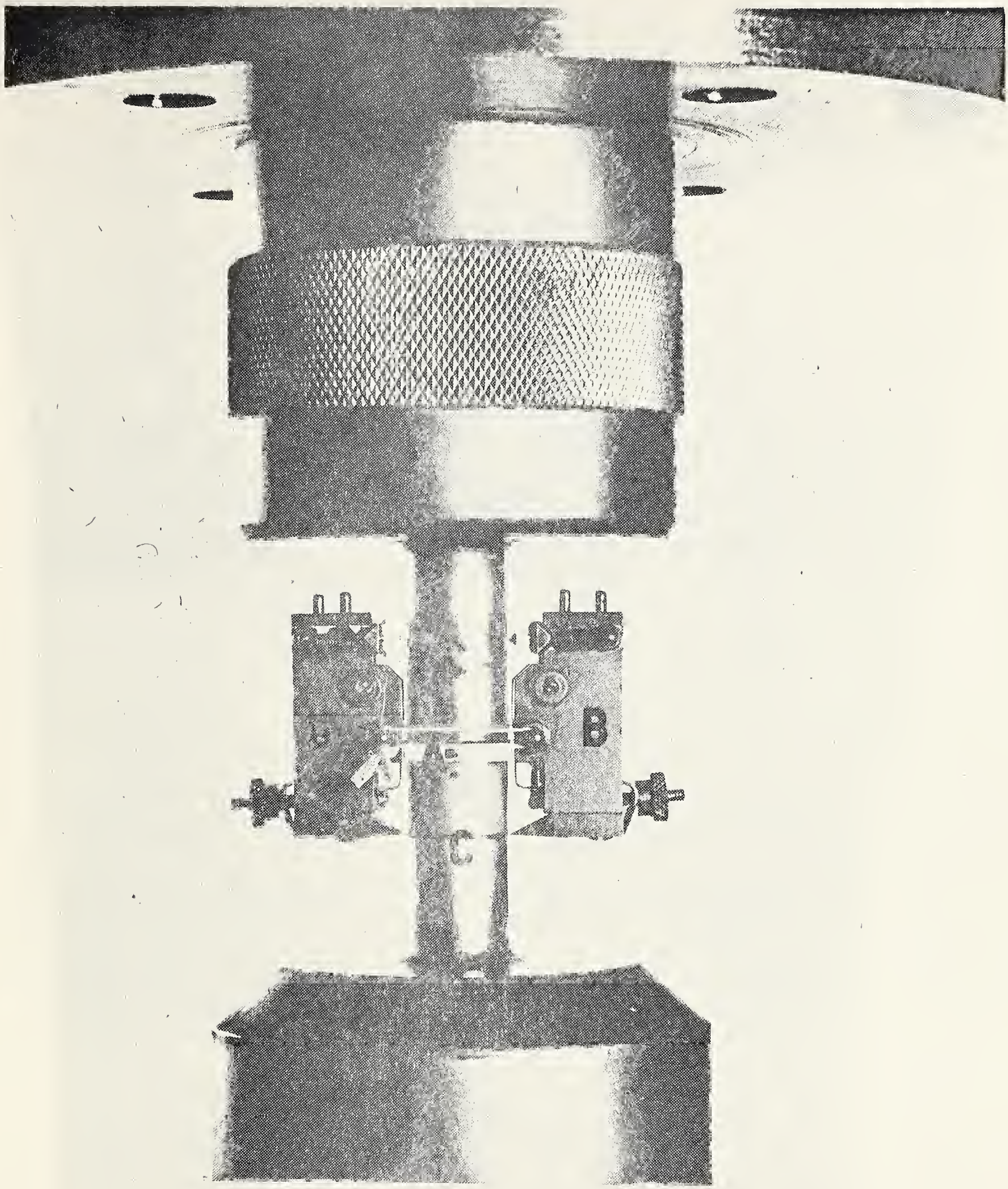

FIGURE 4

Close-up of testing area

A. Tooth specimen

B. Strain gauges

C. Platens

FIGURE 5

Bicuspid

A. Cusp

B. Incisal edge

C. Labial side

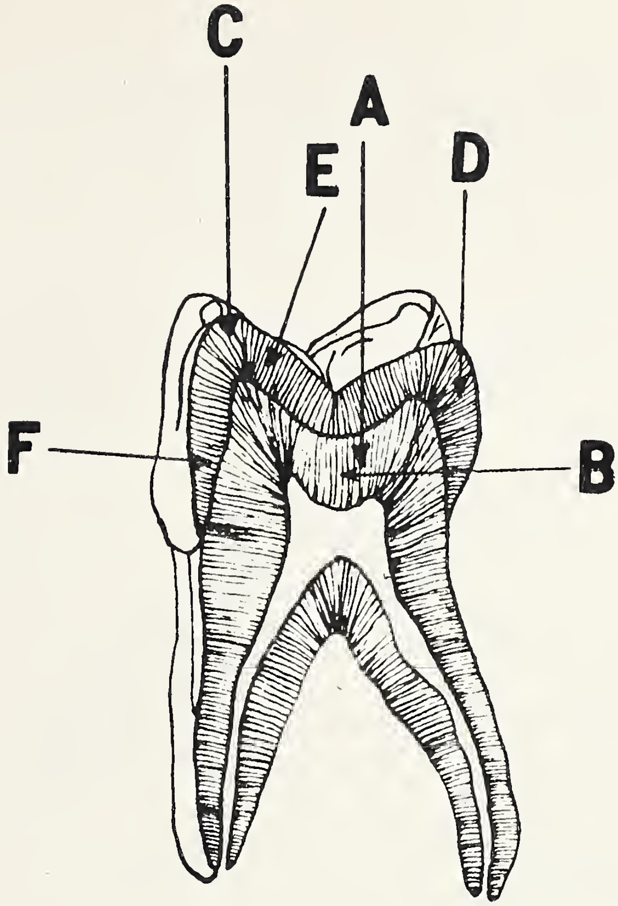

FIGURE 6

Molar

A. Longitudinal sectioning of dentin

B. Transverse sectioning of dentin

C. Enamel, cusp

D. Enamel, side - longitudinal sectioning

E. Enamel, occlusal

F. Enamel, side - transverse sectioning

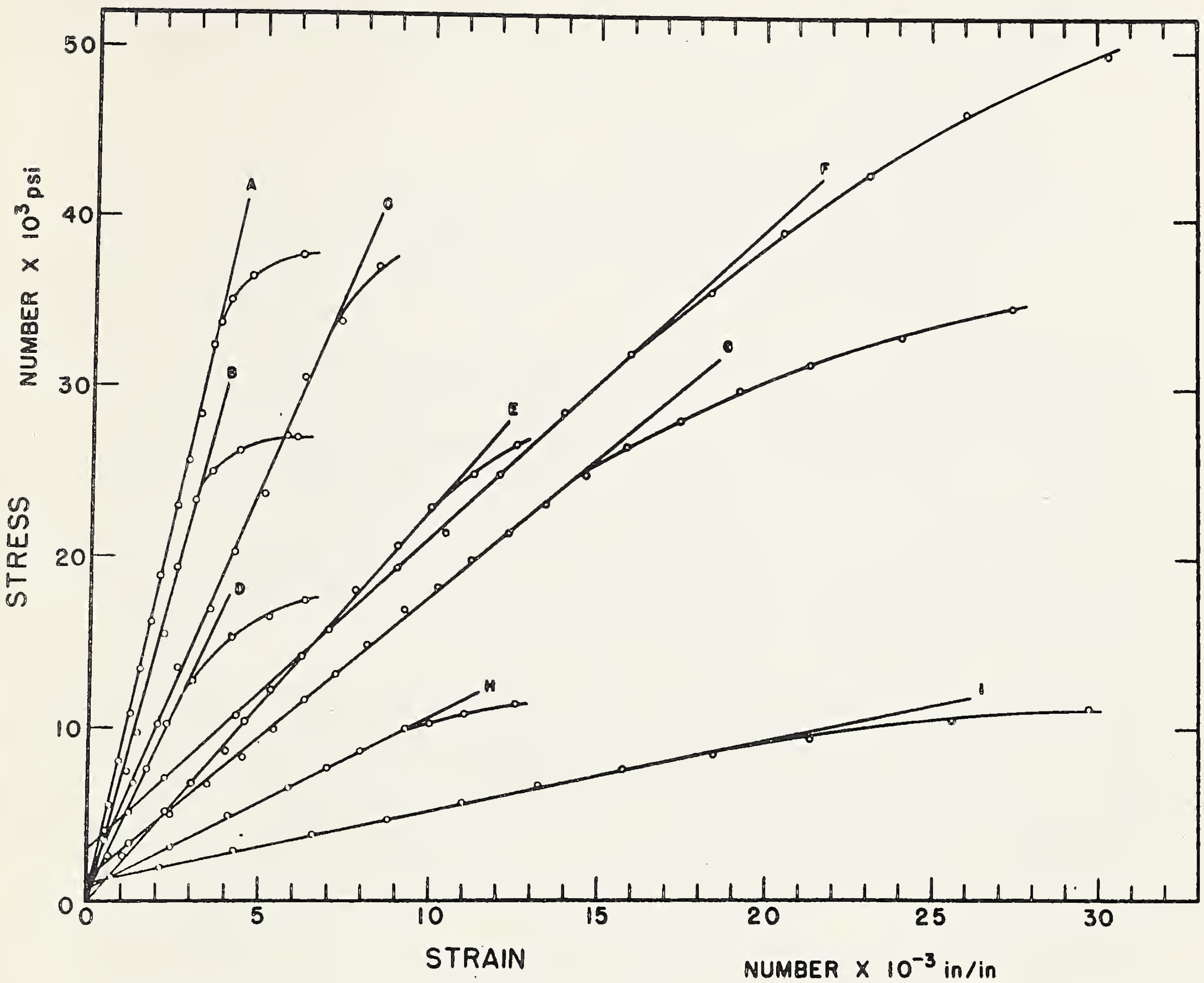

FIGURE 7

Stress-strain diagrams of tooth tissues and some restorative materials

A. Hard inlay gold alloy

B. Medium inlay gold alloy

C. Enamel, cusp

D. Soft inlay gold alloy

E. Silicate cement

F. Amalgam

G. Dentin

H. Zinc phosphate cement

I. Direct resin filling material

U. S. DEPARTMENT OF COMMERCE
Lewis L. Strauss, *Secretary*

NATIONAL BUREAU OF STANDARDS
A. V. Astin, *Director*

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