The measurement of human oral forces*

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This paper reviews the types of instruments used and problems encountered in the measurement of human biting forces. A new instrument, developed for this purpose, which employs strain gauges mounted on a cantilever bridge bite element is described. Associated circuitry, which includes a Wheatstone bridge, amplifier, and integrator, is described. The integrator enables the investigator to record accumulative force over time. Biting force values recorded at five different areas of the mouth are presented from 11 male and 8 female Ss.

Several techniques have been described for the measurement of human biting forces. The instruments developed for this purpose have been referred to as gnathodynamometers (gnatho from Greek, meaning jaw). This paper reviews the types of instruments developed to date and describes a recently developed instrument which overcomes many of the problems found in earlier gnathodynamometers.

The earliest, and perhaps most novel, method employed to determine maximum human biting forces was that of J. R. Patrick (see Klaffenbach, 1936) in the early 1890s. The average force required to crush several different types and sizes of nuts was determined by the use of a "crushing machine." Estimates of biting forces were then made after human Ss attempted to crush different sizes and types of nuts between their teeth.

Black (1895) and Johnson and Hatfield (1917) developed gnathodynamometers which mechanically indexed the bending of spring steel arms which were bit upon by the Ss (see illustration in Fig. 1). However, several problems associated with their usage were noted. Black recognized that biting forces depended upon the vertical separation of the teeth and reasoned that full muscle force could not be exerted with the mouth open widely. He also reported difficulty in keeping the bite pads thin, yet strong enough to prevent breakage. A bite block thickness of 18 mm was required to prevent breakage. [The ideal bite plate thickness for measurement of biting forces has yet to be determined. The

proper thickness may depend upon the parameters under investigation. Data presented by Boucher, Zwener, and Pflughoeet (1959), however, suggest that between-S variability in maximum force measures increases as vertical separation increases; thus thin bite plates seem preferable to thick plates.]

Black further noted that the load exerted upon the bite plate was not distributed evenly across the occlusal surface of the teeth. He observed that the buccal cusps of the bicuspid and molars received the most stress. Further problems were noted in motivating the Ss to exert full stress. The Ss fear of breaking teeth, pain, and the condition of the Ss periodontal tissue were felt to hinder accurate measurements of maximum

force capabilities. The exact positioning of the bite pads between the teeth was also found to influence force measures due to different leverages at the extremities of the bite plate.

An apparatus developed by Boos (1940) overcame many of the above problems but was usable only with Ss having full upper and lower dentures. Major advances in gnathodynamometer designs were made as variable inductance and wire strain gauges became available. Howell and Manly (1948) developed a variable inductance-type strain gauge (Fig. 1) with interchangeable bite plate elements; these allowed changes in vertical dimension to be made and a wide range of forces to be measured. Biting forces applied to the spring steel plate moved a silver foil near a small inductance coil, thus varying the inductance of the coil. A grid dip meter-type circuit converted the variation in inductance to a dc current which was used to indicate biting force. The thickness of the bite element was reported to be 6 mm before adding cushioning materials. The same principles were employed in the design of a small gnathodynamometer, developed by Howell and Brudevold (1950), which was inserted under an artificial tooth. This instrument allowed investigators to record force information without interfering with normal chewing. Strain gauges installed on cantilever

Fig. 1. Four gnathodynamometer types developed to measure human biting force. The upper left-hand instrument was employed by Johnson and Hatfield (1917). Black's 1895 gnathodynamometer is pictured in the upper right-hand corner. A cantilever beam type of instrument employed by several investigators is diagrammed in the lower left-hand corner. Arrows point to the bite pads on each of these instruments. Howell and Manly's (1948) variable inductance strain gauge gnathodynamometer is diagrammed in the lower right-hand corner. The spring plate with bite button is inserted into the grooves in the inductor housing. Biting force is applied directly on top of the inductance coil. The gnathodynamometers are not pictured to actual scale.

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Fig. 2. Portable gnathodynamometer. See text for construction and operating details.

beam arrangements (Fig. 1) have been successfully employed by several investigators (Boone, 1962; Vail, 1970; Bowman, 1970); however, the construction details of these instruments are not readily available.

More recently, small strain gauges have been mounted within a single tooth. Anderson (1956) described an apparatus and procedure for measuring whole-tooth loads using strain gauges mounted within the tooth where previous restorations had been made. Scott and Ash (1970) have reported the development of a small transmitter the size of a molar tooth crown which transmits information from eight sensors mounted within the occlusal surface of an artificial molar tooth.

For purposes of our research, a gnathodynamometer with an extremely thin bite plate was required. We needed a device which could be used with Ss having natural dentition and which did not require modification of the existing dentition. The within-tooth or under-tooth techniques (Howell & Brudevold, 1950; Anderson, 1956; Scott & Ash, 1970) appeared ideal in that they require the least vertical separation of the teeth; however, they require considerable time and skill to install and generally require modification of the dentition. Other gnathodynamometers have bite blocks requiring a vertical separation in excess of 6 mm. Attempts in our laboratory to reduce the thickness of the bite pads on cantilever beam-type

gnathodynamometers to less than 6 mm were unsuccessful. A cantilever bridge design, however, was found to work well with two thin (1-mm) beams.

The instrument (Fig. 2) described below consists of a cantilever bridge and strain gauge arrangement with a bite plate thickness of 2.5 mm prior to cushioning. Associated circuitry, consisting of a Wheatstone bridge, dc amplifier, and meter, is described. Also described is an integrator circuit which allows the measurement of accumulative force over time.

APPARATUS

Bite Plate Element

Construction of the bite element was simplified by using Sklar Model 160-135 forceps (38-04 Woodside Avenue, Long Island City, New York), modified to form a dual cantilever bridge arrangement (Fig. 3). A fulcrum was added, and the forceps points were rounded and permanently closed with a screw and nut. Small strain gauges were mounted using Eastman 910 cement (BLH Electronics, Inc., Waltham, Mass.) to both sides of one of the forceps' handles (Fig. 3). The two gauges form two legs of a Wheatstone bridge (Fig. 4). Employing the gauges in this manner doubles the gauge factor and provides temperature compensation. A positioning arm was attached to and protruded from the focal point wedge screw. This positioning arm was found useful in replicating the exact placement of the bite element in the mouth, thus assuring that the biting force occurred at the same location on repeated measurements. Several bite plate cushioning materials were examined and rejected. It was found that most common plastic and rubber materials were inadequate, as they were too

easily pierced by the teeth. Bowman (1970) reported using a nylon material (type and source not specified), which may be usable but was not examined in our laboratory. We found that 7 x 7 mm dental cottonwood dental sticks (Dixon, S. S. White Dental Manufacturing Co., Los Angeles), cut in half and reduced in length to 20 mm, provided a 2.5 x 7 x 20 mm cushion which, when soaked in water for 1 h prior to usage, had excellent cushioning properties. The relatively soft wood compresses when bit upon and forms itself to the topography of the tooth without splitting or being pierced. Wood cushions placed on both surfaces of the bite element were held in place by a thin plastic tube, 8 mm in diam, slipped over the end of the bite element. The element thickness with the wood cushioning materials was 7 mm and the width was 7 mm. A width of 7 mm was found to bridge both cusps of most teeth, while not interfering with adjacent teeth. Disposable latex finger cots (Bittner brand, No. 610 small, New York) were slipped over the end of the bite element. These eliminated the need for sterilization procedures between uses.

The bite element described above was found useful in measuring forces of up to 140 lb. Bite elements capable of measuring up to 200 lb have been made in our laboratory using the same principles, i.e., converting forceps into dual cantilever bridge assemblies.

Associated Circuitry

The Wheatstone bridge, amplifier, integrator, and meter circuitry (Fig. 4) were designed, using common inexpensive linear integrated circuits. All components were wired on a vector board and mounted in a 10 x 16 x 5 cm meter box (Calectro Type J4-726). The Wheatstone bridge

Fig. 3. Detailed drawings of dual cantilever bridge bite element. Two strain gauges are mounted on either side of the forcep's handle, which was reduced in width at Point A. A positioning arm (Point B) protrudes toward the bite surface (Point D). A wedge mounted at Point C works as a fulcrum. Force applied at Point D is transferred to Point A and sensed by the two strain gauges. A three-wire shielded cable connected the two strain gauges to the Wheatstone bridge and amplifier network.

Fig. 4. Circuit diagram of gnathodynamometer. The two Type FAE-06N-1256EL (SR-4) strain gauges (BLH Electronics, Waltham, Mass. 02154) are mounted on the bite element. The dual 747 operational amplifier may be replaced with two 741 amplifiers. Batteries B1, B2, and B3 are 9-V transistor radio batteries (Eveready No. 216). Meter M1 is a Caletro No. D1-912 milliammeter. Resistance values are shown in ohms except where noted. The 773 $\pm 1\%$ resistors in the bridge network may be replaced by other paired precision resistors ranging from 100 to 1,000 ohms. Boxed lettering indicates front panel controls.

network, including a 2-ohm calibration resistor and switch (lower left-hand corner, Fig. 4), fed into a high gain inverting operational amplifier. The 10k-ohm dc offset potentiometer is used to compensate for slight imbalances in the Wheatstone bridge and serves as the meter zero control. An 8.2k-ohm resistor in parallel with the 1k-ohm zero control reduces the control's sensitivity. A 1-megohm potentiometer in the feedback loop adjusts the gain of the amplifier. The meter amplifier (upper right-hand corner, Fig. 4) is a fixed gain inverting amplifier. The 10k-ohm dc offset potentiometer was adjusted for a 0-m output reading, with Pin 7 grounded via a 10k-ohm resistor. Three ranges of sensitivity are provided by the three resistors which are switched in series with the milliammeter. A dc output jack allows the unit to be used with a chart recorder when permanent records are required.

An integrating amplifier circuit (lower right-hand corner, Fig. 4) is switched into the meter circuit when the function switch (S4) is in the integrate mode (Int). This circuit has a dc output proportional to the time integral of the input

$$E_{out} = -\frac{1}{RC} \int E_{in} dt.$$

The "characteristic time" of the integrator, i.e., the time required for the output to change by an amount equal to the average value of the input, is 80 msec ($T = RC$). The "run-set" switch is used to reset the integrator. With the switch in the "set" position, the stored charge across the 8-microF capacitor is reset to zero. In the "run" position, the circuit performs as an integrator. The "zero" adjust control must be set such that with no biting force applied and the "run-set" in the run position, the meter will remain at zero. The 1k-ohm dc offset potentiometer is adjusted such that the integrator output remains at zero with no input signal applied.

Calibration

The completed gnathodynamometer (Fig. 2) was calibrated, using an Instron Tensile Testing Instrument, Type TT-B-L (courtesy of Materials Department, School of Engineering, UCLA). With the two power switches (S1 and S4) on, the "zero" and "gain" controls were adjusted such that, with the 2-ohm calibration resistor in the circuit, the meter (M1) read full scale on the X50 mode and zero with the 2-ohm resistor out of the circuit. These readings were periodically checked and maintained during the calibration procedure. Forces of known value were applied with the

tensile testing instrument through a 4-mm-diam solid metal cylinder centered on the bite plate, 1 mm from the end of the positioning arm. It was originally intended to have the meter read out directly in pounds force; however, it was found that bite elements could not be easily built with a linear force-output function. Furthermore, each bite element displayed a different force-output function, making the use of nonlinear amplifiers impractical. Calibration charts were thus made for each bite element (Fig. 5); this allows the user to convert the gnathodynamometer's meter reading into force values. It was found after repeated calibration checks with known force values that an accuracy of ± 3 lb could be expected. Long-term accuracy is made possible by periodically checking the "zero" and "gain" controls for a zero and full-scale reading. The proper adjustment of these controls compensates for variation in battery voltages. It should be noted that this instrument, as well as earlier devices described above, measures pounds of force applied between two surfaces, not pressure. Pressure is a measure of a force exerted per unit area, with the most common unit being the square inch (psi). Pounds of force measurements are made without reference to area.

Tests of the gnathodynamometer's ability to integrate force over time were made using the same tensile testing instrument. Specific forces were applied over a varied time interval. It was found that the gnathodynamometer did in fact integrate force over time and did so in a linear manner, i.e., 20 lb force for 5 sec produced a meter reading of .10, whereas 20 lb force for 10 sec produced a meter reading of .20. Note that in using the integrate mode the same meter reading may be produced

Fig. 5. Sample calibration chart for gnathodynamometer bite element used in converting milliammeter output to pounds biting force. The upper curve is used for the X50 scale and the lower curve is used on the X100 scale.

Fig. 6. Mean biting forces as a function of five test positions and sex as measured with the gnathodynamometer described in the text. The bite element positioning arm was used to determine exact placement between Ss by positioning the arm into the outer cleavage of the upper teeth at each test point.

in numerous ways. For example, a reading of .80 may be produced by a force of 10 lb applied for 80 sec, 20 lb for 40 sec, or 40 lb for 20 sec, etc. When long-term drift was compensated for by adjustment of the "zero" control, integrated force measures were repeatable to $\pm 2\%$ of the meter reading.

Operating Characteristics and Discussion

The instrument described above was designed to fill the need for a portable, inexpensive gnathodynamometer with a very thin bite element. A thin bite element was felt desirable to closely approximate the vertical jaw relationship during chewing, swallowing, and bruxing. Materials for the instrument cost about \$60. Battery life was found to be 60 h. A nonportable unit for use on 110-V ac power could be built using commercial dc power supplies if portability was not required. Except for battery replacements, no component failures have occurred.

The instrument has been used in our

laboratory to calibrate other instruments designed to investigate human chewing behavior (Rugh, 1971) and to measure biting forces in normal and pathologic populations. Data presented in Fig. 6 are an example of data collected using the gnathodynamometer. Maximum biting forces of 19 healthy adults were recorded at five different positions of the mouth. Sex differences in this sample are apparent; male force values were consistently greater than those of the female. Klatsky (1942) reported finding similar sex differences. Comparison between studies reporting maximum human biting forces must be made cautiously because the measurements are typically made using different apparatuses, procedures, and populations. Brawley and Sedwick (1940) reviewed 27 studies which reported maximum biting force values ranging from 45 to 550 lb in adult populations. Too frequently these reports lack any description of the instrument used. Future reports of biting forces obtained using the above or any other gnathodynamometer

should be accompanied by a detailed description of the bite element employed. Further discussion of the problems and applications of gnathodynamometers may be found in reviews by Haber (1929), Klaffenback (1936), O'Rourke (1949), and Lawson (1960).

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