

Dental holographic interferometry *in vivo* utilizing a ruby laser system

I. Introduction and development of methods for precision measurements on the functional dynamics of human teeth and prosthodontic appliances

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Holographic interferometry, an application of laser technology, was introduced as a non-contact and non-destructive method for investigations concerning the dynamics of human teeth and prosthodontic appliances in function. The method was first tested in a simulator and then used in a number of clinical experiments. A special, totally reflecting paint was used for surface preparation prior to holography. A Q-switched double-pulsed ruby laser with a pulse-length of 24 ns was combined with an electronic subminiature force sensor for pulse triggering which was actuated by the masticatory force of the patient. Force increase and pulse positions were registered synchronously on the screen of an oscilloscope. The applied force exerted by the patient's masticatory muscles could thus be defined according to its point of application, direction, amplitude and duration. The corresponding surface deformation was evaluated by means of a synchronized, double exposed hologram. The measuring range as well as the sensitivity of the method depend on the wavelength of the ruby laser light (0.6943 μm). Conclusions could be drawn regarding the relative and absolute mobility of the teeth and related structures of the holographed jaw section. The technique provided abundant and detailed information, its documentation being facilitated by means of a special photographic method.

Key-words: Holography; interferometry; lasers; tooth mobility

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An important factor within the masticatory function of man is the three dimensional intra alveolar mobility of the teeth. Anatomical conditions, the magnitude and direction of the stress of mastication, the presence of pathological damage in the immediate vicinity of the tooth and

other factors act on the process. Tooth mobility has been studied by means of mechanical as well as non-contact methods (Körber, 1962, 1963; Mühlemann, 1951, 1960; Parfitt, 1960, 1961; Picton, 1964). There have, however, been considerable difficulties in adequately recording the

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complete dynamic pattern of teeth during function, depending on methodological errors and the disturbing effects of technical appliances.

Removable partial dentures as well as fixed bridge-work influence the type and degree of tooth mobility. This is apparently of great importance to the long-term prognosis. Functional mobility of free end removable partial dentures has been registered by means of cineradiography (Hedegård, Lundberg & Wictorin, 1966). The results obtained have been valuable for prognosis judgement and therapy selection in prosthodontics. However, mobility phases of fixed bridge-work are often small and beyond the sensitivity of conventional measuring techniques. This paper will describe a holographic ruby laser system constructed in order to obtain detailed information about functionally conditioned displacements and deformations of individual teeth as well as groups of teeth. The functional dynamics of fixed bridge-work can also be registered by means of this equipment.

The laser phenomenon

In recent years the application of a laser has often been the subject of current interest in various connections. Ever since it was possible to attain a laser effect in a rod of synthetic ruby, (Maiman 1960, Prokhorov, 1958; Townes, 1961) a very rapid development of laser technology has taken place. The good coherence and monochromatism of laser light together with its high intensity and parallel nature have supplied science and industry with new methods and possibilities. In odontology laser techniques have been used to produce physical and chemical alterations (Scheinin & Kantola, 1969; Vahl, 1971; Kantola, 1974) and for precision

measurement in laboratory installation (Wedendal et al. 1972, Wictorin, Bjelkhagen & Abramson, 1972). The present investigation is based on an application of the branch of laser technology known as holographic interferometry. A short description of these techniques is given below.

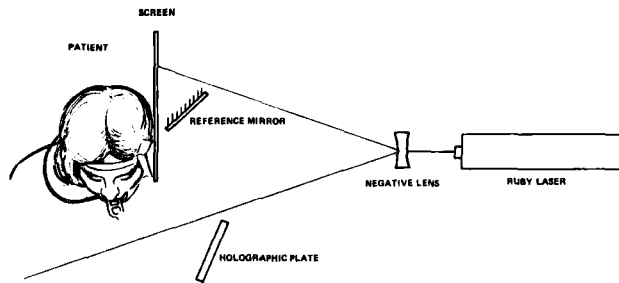
GENERAL METHODOLOGY

Holographic interferometry

The holographic method. The holographic method was described by Gabor (1948). »Holos» means »whole, complete», and refers in this connection to the creation of a total, three-dimensional picture of the object. When the continuous emission He-Ne-laser was developed in 1962, the holographic technique began to be used for practical purposes (Leith & Upatnieks, 1964). A *hologram* is a high resolution photographic plate, in which both intensity and phase information have been stored. Together this information completely describes the three-dimensional extension of an object.

The three-dimensional image. The registration or recording of a hologram is obtained in the following way: A laser is caused to illuminate the object for a certain time, (time of exposure) (Fig. 1). The laser beam is expanded by means of a spatial filter placed between the laser and the object. A reference mirror is introduced into the system in such a position that part of the expanded beam, the reference beam, is reflected from the spatial filter towards the holographic plate. Another part, the object beam, or signal beam, reaches the holographic plate after being diffusely reflected by the object. The interference between the signal beam and the reference beam creates a unique pattern

Fig. 1. Experimental arrangement for clinical research. The wavefronts of laser light reflected via the patient and the reference mirror create a unique interference pattern in the holographic plate.



in the film emulsion. This is called *the primary interference pattern*. When the hologram has been developed and fixed, it is replaced in the system and illuminated with the reference light from the laser. This procedure is called *the reconstruction of the hologram*. (Fig. 2.) A three-dimensional *virtual image* of the object can now be perceived when looking through the holographic plate. If the eye is moved in different directions along the

surface of the holographic plate, the image will appear as if the object had been »behind» the plate in the same position as during the registration. Even a small piece of the holographic plate contains sufficient information to create a picture of the whole object. This is due to the fact that the light has been reflected during the registration from each visible point of the object to each point of the holographic plate. The plate contains a

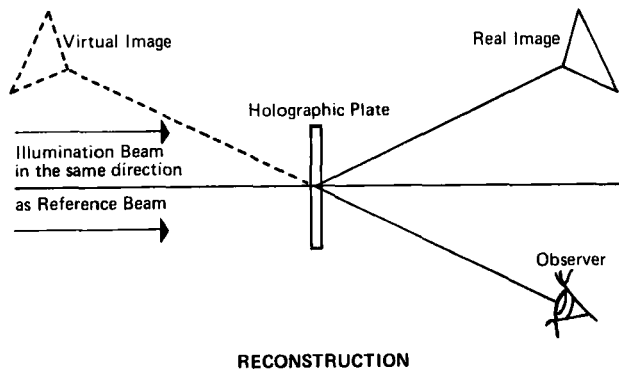
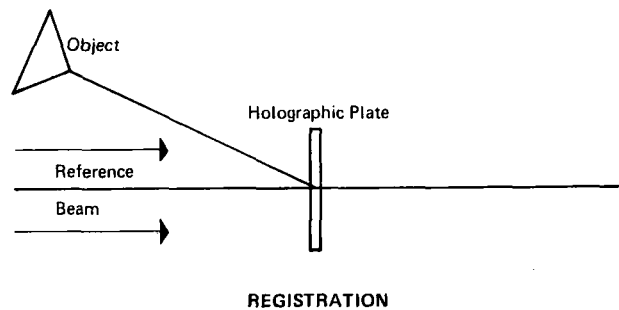


Fig. 2. Registration and reconstruction of a hologram. At the reconstruction two different diffracted outgoing wave fronts are created. The complex conjugate wave front $R \cdot R^* \cdot O^*$ gives rise to a real image of the object on the same side of the holographic plate as the observer. The wave front gives rise to a virtual image which seems to come from the place where the object was positioned during the recording.

coded storage of wave fronts from the object in respect of amplitude as well as phase. The holographic technique can be used in different ways for precision interferometric measurements (Brooks, Heflinger & Wuerker, 1965). If holography is carried out by means of a continuous laser, the test arrangement must be vibration free (vibration amplitude $< \frac{\lambda}{8}$) to obtain a hologram of high quality.

For this same reason very rapid laser pulses ought to be selected for holographic interferometry investigations in vivo in order to eliminate the disturbing effects from inevitable object movements.

Holographic interferometry with double exposure technique. If the film plate is exposed and then the object subjected to a load, an exact measure of the deformation produced by the load can be obtained by repeating the exposure on the same plate after deformation. A displacement pattern, the secondary interference pattern, in the form of alternately bright and dark fringes will arise in the image due to the wave fronts of the laser light alternately intensifying and extinguishing each other. This technique is called double-exposed holography. The angle of incidence and observation, the wave-length of light and the number of interference-fringes in the image determine the amount of deformation for the applied load.

Real-time holography. With another technique, real-time holography, it is possible to obtain an interference pattern utilizing a single-exposed plate. After development the plate is exactly repositioned in the system. The virtual image of the object will interfere with the object itself, if a suitable deforming load is applied. The interference pattern depends on the amount of load on the object.

Time average holography. Time average

holography has been used for vibration studies (Powell & Stetson, 1965).

A brief mathematical description of the holographic principle. The intensity of a light source I can be expressed as the amplitude a of the light wave times its complex conjugate a^* . That is

$$I = a \cdot a^*.$$

Letting R indicate the reference beam and O the object beam, the light intensity on the holographic plate can be expressed

$$I_h = (R + O)(R^* + O^*) = R \cdot R^* + O \cdot O^* + R \cdot O^* + O \cdot R^*.$$

Note that

$$R \cdot R^* = I_R \text{ the intensity of the reference wave}$$

$$O \cdot O^* = I_O \text{ the intensity of the object wave}$$

$$I_h = I_R + I_O + R \cdot O^* + O \cdot R^*.$$

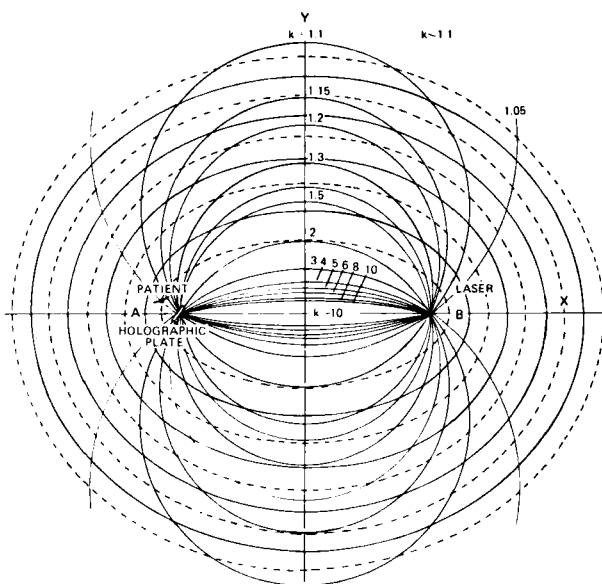
At the reconstruction of the hologram the plate is illuminated with the reference light R and the light transmitted through the holographic plate

$$T_h = I_h \cdot R = R \cdot I_R + R \cdot I_O + R \cdot R \cdot O^* + R \cdot R^* \cdot O.$$

RI_R and RI_O are unmodulated illumination intensities but $R \cdot R^* \cdot O$ can be written $I_R \cdot O$, or the reference intensity modulated by the object amplitude; clearly this is an optical rendition of the object. This is a virtual image of the object. The $R \cdot R \cdot O^*$ is the real or conjugate image of the object. The presence of both a real and virtual image is characteristic of all holographic processes, but usually the recording geometry is arranged so that the real image does not interfere with the virtual image appearing to exist behind the plate.

The holodiagram. The evaluation of a holographic interferogram can be performed with the formula

Fig. 3. Position of the experimental equipment in the hodiagram. The hodiagram (Abramson, *loc. cit.*) was developed in order to facilitate the registration and evaluation of holograms. It is made up of ellipses of constant path length for the light that passes from B (the virtual focus of the negative lens in front of the laser) to A (the centre of the holographic plate) via the patient. The position lines of constant distance between ellipses are formed by arcs of circles named k-lines. In this case the k-value is about 1.05.



$$d = n \cdot \frac{2}{\cos \alpha + \cos \beta} \cdot \lambda$$

d gives the amount of deformation if

n is the number of dark fringes

α is the angle between surface normal and the line of illumination

β is the angle between surface normal and the line of observation

λ is the wave-length of the utilized laser light

In order to facilitate the registration and evaluation of holograms the hodiagram was developed (Abramson, 1969).

The hodiagram (Fig. 3) consists of ellipses representing loci of constant pathlength for the light transmitted from the source B to the observer A via the object C. The circles represent loci of constant distance separating adjacent ellipses. The displacement d is calculated from the formula

$$d = n \cdot k \cdot \frac{\lambda}{2}$$

k is obtained from the diagram.

Evaluation of relative and absolute object displacement. Object displacement is defined as the difference in the three-dimensional position of one particular point of the object surface e.g. a cusp of a tooth. During the experiment the position at the first pulse and the second pulse is recorded. The hologram contains information regarding all surface displacements that have happened during the increase of a force having a well defined point of application, direction, amplitude and duration. This information makes it possible to evaluate the mobility pattern of different parts of the object e.g. the mobility of a tooth, a group of teeth or a prosthodontic appliance.

The muscle activity during mastication is estimated to cause two types of displacements. »The absolute displacement» is defined as the displacement of the cranium in relation to the holographic set up, while »the relative displacement» is defined as the displacement of one tooth or a group of teeth in relation to the

surrounding tissue. Two different methods can be used for the evaluation (*Abramson*, 1970, 1972).

Static evaluation. Static evaluation is used to determine motions in a direction that bisects the illumination and observation direction. The number of ellipses in the holodiagram intersected during the delay between the two pulses is used to determine the magnitude of the displacement.

Either the hologram or a photographed reconstruction can be used for the static method. In this method the hologram is examined from only one position. The number of interference fringes on the part of the object which is to be evaluated is compared to the number of interference fringes on the surrounding parts of the object. The difference in number of fringes reveals the amplitude of displacement with a resolution $k \cdot \frac{\lambda}{2}$.

The direction (+ or —) cannot directly be interpreted from the fringe pattern. To solve this problem further experiments were made using the simulator.

Dynamic evaluation. Dynamic evaluation is used to determine the motion in a direction that is at right angles to the observation direction. The reconstructed double exposed hologram itself is needed for this evaluation, the real object being removed.

The eye is moved around while the reconstructed object is observed through the holographic plate. Doing so the observer sees the fringes move in respect to the virtual image of the object surface. A maximum motion of fringes is found for a certain direction of movement of the eye along the plate. This direction is identical to the motion of the object between the two exposures.

The dynamic evaluation is needed to

extract an optimal amount of the information stored in the holographic plate. Not only the direction but also the amplitude of the displacement can be found in this way.

It has been possible to discriminate between the absolute displacement and the relative displacement using a combination of the two methods. This is of fundamental importance for the application of the holographic results to a tooth.

MATERIAL AND METHODS

Ruby laser Holobeam 651. Double-pulsed holographic system model 651* is a ruby laser intended for holography (Figs. 4 & 6). It is constructed to emit a single pulse or a double pulse with adjustable delay between the pulses.

The ruby laser consists of an oscillator and an amplifier. The oscillator or the laser unit consists of a rod made of synthetic ruby (Al_2O_3 with traces of Cr_2O_3) surrounded by a helical xenon arc-discharge lamp. A rear mirror and a front mirror with a line selector and a spatial filter create appropriate coherence. Pockels cell functions as a Q-switch for pulsing the laser. In front of the oscillator unit there is another ruby rod surrounded by a helical xenon arc-discharge lamp. This ruby rod serves as amplifier. A schematic diagram of the laser is shown in Fig. 4.

The Q-switch functions as follows: at a certain moment, the light path is opened to the rear mirror through the Pockels cell for 24 ns. It is then possible for the ruby to lase, or fire. At the second pulse the opening of the cell is repeated after a pre-set delay. The delay between the

* Holobeam®, Inc., 560 Winters Avenue, Paramus, New Jersey, U.S.A.

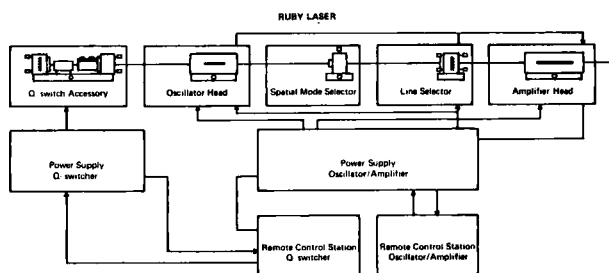


Fig. 4. Schematic diagram of the ruby laser Holobeam 651.

pulses can be varied electronically from 200 to 500 μ s. The line selector, a double-sapphire etalon assembly, selects the wave-length at which the oscillator operates (6943 Å). The beam is amplified about sixfold by the amplifier. In addition to the optical units the system is provided with two power supply units, one for the flash lamps and one for the Q-switch, and two control stations.

At the control station of the oscillator and the amplifier the desired voltage of the capacitor bank is set. From this station the loading and firing processes are also controlled. At the control station of the Q-switch the voltage to the Pockels cell and the delay between the lamps being lit and pulsing; and at the second pulse, the delay between the pulses are adjusted. A single or double pulse is also selected from this station.

Pockels cell and Q-switching operation. The Pockels cell assembly contains a KD*P (KD_2PO_4) crystal (potassium dihydrogen phosphate) in an index-matching fluid cell; a polarizer; and a maximum-reflectivity dielectric mirror. When the lamp in the oscillator laser head is fired, the cell is cross-polarized with the polarized light from the laser rod (i.e. the cell is »off») and lasing action is temporarily inhibited. After a set delay time (controlled by the Pockels cell remote station) during which the population inversion

of the excited chromium ions within the ruby rod rises to extremely high levels, a high voltage pulse is applied to the crystal. This causes a 90° rotation of the plane of polarization, the cell becomes »open», and lasing of the excited chromium ion occurs in a »giant pulse» of 24 ns duration. The voltage applied to the crystal then decays and the plane of polarization returns to its blocking condition. When the Pockels cell is set for double-pulsed operation, the action can be repeated after a preset time delay, provided that these time delay is sufficient to build up the population inversion high enough for the second pulse to equal the first in intensity.

Subminiature pressure sensor — force sensor. The subminiature pressure sensor used was a Kyowa type PS — 10 KA*. It consists of a metal cylinder closed at both ends with the diameter 6 mm and the height 0.6 mm. One of the flat end surfaces is very thin and easily deformed by pressure. Inside it are attached four extremely small strain-gages which are connected to a bridge circuit. The strain-gages are made of metal, which in combination with the full bridge arrangement provides the least possible influence of temperature on the measuring results.

In the present investigation a force

* Kyowa Electronic Instruments Co Ltd, Tokyo, Japan.

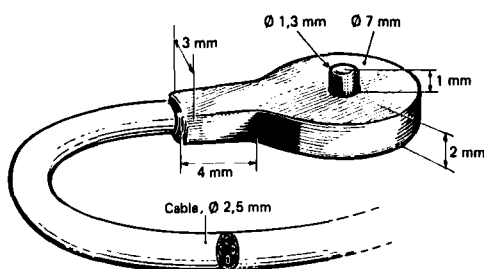


Fig. 5. Subminiature force sensor. The masticatory force is concentrated to one point of application during the experiment by means of the vertical metal rod.

sensor was required (Fig. 5). In order to transform the sensor from pressure sensor into force sensor it was placed in a hollow cylinder made of steel. This was closed with a cover of about 0.2 mm thickness. A central steel rod of about 1.3 mm diameter and about 1 mm height projects perpendicularly to the cover. The masticatory force is to be applied axially to the tip of the rod so that the cover is point loaded. The pressure sensor is located in the hollow cylinder so that the thin diaphragm of the sensor is deformed simultaneously with the cover of the cylinder. A soft epoxy cement serves as a medium for distributing the force. The diameter of the cylinder is about 7 mm and its height about 3 mm including the rod. It is provided with a cable shield of about 4 mm length made of steel and having a rectangular section of about

2×3 mm, through which is introduced a specially manufactured shielded four-wire conductor having a diameter of 2.5 mm. The subminiature pressure sensor is supplied with a stabilized voltage of 3 volts.

The output signal from the sensor is the unbalance voltage produced in the measuring bridge by deformation. It has a maximum value of 1mV per volt from the voltage supply. A DC amplifier made by Vibro-meter (type DCA-1/AP) is used as an amplifier for the output signal. In this system, the output signal is connected to one channel of an oscilloscope. For reduction of noise from the sensor and the amplifier an integrating filter with a time constant of about 0.1 ms is used.

Calibration of the sensor was made by loading with known weights and making suitable to the amplification. Calibration was established at 0.8N/scale division on the vertical axis of the oscilloscope screen.

Optical detector. For registration of the laser pulses a photo detector of the silicon type (Siemens BPY-64)* was used. It was placed so as to be illuminated by the laser beam. The signals were recorded on the second channel of the oscilloscope.

Oscilloscope. A two-channel storage oscilloscope (Tektronix, model 549)**

* Siemens A.G., Munich, West Germany.
** Tektronix, Inc., S. W. Millikan Way, Beaverton, Oregon, U.S.A.



Fig. 6. Interior of ruby laser room with simulator arrangement. Seen from the left are: remote control station for the laser, oscilloscope with a polaroid camera, holder for the holographic plate, laser light detector, reference mirror and ruby laser head.

was used. Since the flash duration of the helical xenon arc-discharge lamp in the ruby laser was about 1 ms a velocity of 200 $\mu\text{s}/\text{cm}$ in the horizontal axis of the oscilloscope was used.

Ruby laser system

Laser rod, oscillator: 3.00" \times 0.375" ruby
 Laser rod, amplifier: 6.00" \times 0.375" ruby
 Rear reflector: Flat
 Output reflector: Double tuned etalon
 Pockels cell crystal: KD* P
 Power supply: 10 kV variable
 Capacitor bank: 100 μF
 Output energy: 0.150 J
 Pulse width: 24 ns
 Peak power: 6.5 MW
 Wave-length: 6943 Å
 Line width: 0.006 Å

Holographic material

Agfa Gevaert Scientia 10 E 75¹⁾
 Sensitivity: 50 erg/cm²
 Resolving power: 2800 lines/mm
 Support: Glass plates 1.2—1.4 mm
 Size: 9 \times 12 cm
 Thickness of emulsion: 7 μm
 Developer: G 150
 Fixer: G 334

Simulator tests

Purpose of the simulator tests. The purpose of the simulator tests can be summarized as follows:

1. To determine the correct position of the object and the equipment in the holodiagram.
2. To make fine adjustments to the test device *before* experiments in a biological environment, thus saving the patient from unnecessary time waste during the clinical experiments.

3. To study the different test variables and their interrelations. Example: Selection of suitable force level, sweep rate and pulse delay.

4. To develop a method for surface preparation of the teeth etc., so that optimal visibility was obtained in the interference pattern of the hologram.

5. To study the obtained holograms with respect to quantity and type of information.

6. To facilitate the evaluation of the holograms. The mere mechanical illustration in a simulator of the function *in vivo* can be of great value for the definition of, for example, the direction of force vectors.

Method development in simulator tests.

As preparation for experiments in a biological environment a test device was assembled with the intention to simulate the masticatory system of man. A pair of model sets of teeth (Frasaco)* made of acrylic material and with the teeth individually screwed on to the base were fixed in an articulator of the type Dentatus ARL** (Fig. 7). The degree of mobility

* Franz Sachs & Co., 7992 Tettngang, West Germany.

** AB Dentatus, Stockholm, Sweden.

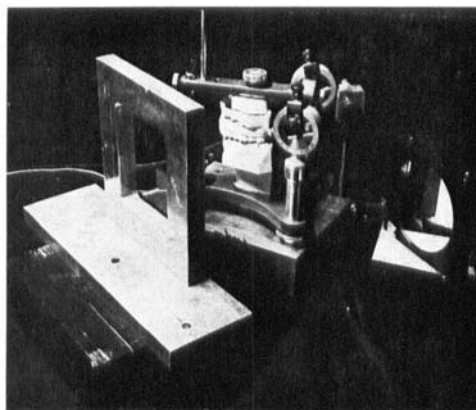


Fig. 7. Simulator arrangement. Seen from the left are: holder for the holographic plate, simulator with force sensor in position, laser light detector and reference mirror.

¹⁾ Agfa Gevaert, Belgium.

of each tooth could be varied by tightening the axial fixing screw differently.

Acrylic material as well as living oral tissue has a certain degree of transmittance depending on the particular type of laser light used. For this reason it was necessary to develop a method for surface preparation prior to holography in order to obtain optimal visibility of the interference fringes in the hologram. Several types of available plastic paints were tested. The best results were, however, obtained using a special paint composed of gold dust, resin, CaOH_2 and chloroform. This paint reflected the laser light totally.

The simulator arrangement was placed on a rubber plate on the holographic table in correct relation to the ruby laser, the reference mirror and the hologram holder, according to the principle of the holo-diagram. The resilience of the rubber caused a slight movement in the arrangement during the tests — corresponding to the patient's head movements. A number of tests were carried out, in order to establish a technical routine for interference holography.

In analogy with a planned patient test the mobility of an artificial tooth was examined as is described below: The electronic force sensor was inserted between the left maxillary first premolar (tooth 24) and its antagonists in such manner that the vertical rod rested with its tip in the distal fossa of the occlusal fissure. The lower cylinder surface of the sensor lay close to the teeth in the lower jaw. The sensor was connected to the ruby laser via the oscilloscope and calibrated so that the first pulse of the ruby laser was to be released at a force of 2N. This force level for pulse triggering seemed to be adequate with regard to biological conditions. The sweep rate of the oscilloscope

was experimentally varied. A 200 $\mu\text{s}/\text{cm}$ scale was chosen on the oscilloscope (horizontal) screen so that the laser pulses were distinctly positioned in the coordinate system. The force curve related to the pulses at the chosen sweep rate gave exact information about force increase between the pulses. The hologram plate was placed in the holder and the test was carried out in dark room lighting. Finger pressure was exerted on the upper movable part of the simulator. When the force level reached 2N the first laser pulse was released. After 450 μs a second pulse of the same intensity as the first was released automatically.

The time interval between the pulses could be varied as described in the section »Ruby laser Holobeam 651». The pulses were registered by an optical detector connected to the oscilloscope as described earlier.

The whole sequence was drawn briefly on the screen of the oscilloscope, which was photographed immediately after each test with a polaroid camera. Force curve and pulse position for each hologram were thus obtained. In the hologram was stored all the information about the deformation process that took place between the two laser pulses. By repeating the test under systematically varied basic conditions, conclusions about simulator function could be drawn after comparisons were made.

Clinical experiments

Consideration was given to the utilization of ruby laser light in clinical experiments. According to the simulator tests holography will expose the patient to a 75 mJ pulse of energy. This quantity is not dangerous for living epithelialized tissue. Repeated exposures do not have an additive effect (*Tengroth, 1973*).

However, if the eyes were directly exposed to this intensity of laser light severe retinal burns would result. In these experiments the eyes were completely protected by means of black glasses, having no transmittance for light. A black wooden screen protected the face, leaving the jaw section exposed. Holography was performed with the same geometry in the holodiagram as in the simulator tests (Figs. 1, 3 and 10).

1 ml* of Skopyl*** was injected about 20 min before the registration in order to inhibit salivation. For the development of clinical methods a female patient, 60 years old, was holographed in a series of 10 holographic plates (Fig. 8). Her dentition was 47 . . . 37 in the lower jaw and 17 . . . 25 in the upper. All teeth were very firmly attached to their sockets and no visible clinical mobility could be recorded.

In analogy with the earlier simulator test, 24 was chosen as the tooth to be examined holographically. Later a saddle-extension bridge will be constructed with 24 and 25 as abutments. Repeated holographic registration of the jaw section will be performed with the bridge in situ. The patient's lips and cheek were retracted by means of a translucent flat acrylic hook. The jaw section to be exposed was painted with gold paint which was of a fast drying type. The laser light was totally reflected by means of the paint. The paint could be easily removed after the experiment by the careful use of chloroform as a solvent.

The cable of the subminiature force sensor was attached to an upper incisor by means of waxed silk ligature. The sensor was positioned in such a manner that the masticatory force was concentrated in the

* 0.5 mg/ml.

** Pharmacia, Denmark.



Fig. 8. Test person prepared for holography. The region to be exposed is covered as described separately with special paint for total reflexion of the laser light. The subminiature force sensor is positioned between 24 and its opposing teeth. During the registration of the hologram the eyes of the patient are protected by means of black glasses.

vertical rod, which was cemented in the distal fossa of 24 by means of acrylic cement. During the cementing the opposing teeth to be studied were kept simultaneously in contact with the lower metal surface thus preventing bending and tilting of the sensor during the experiment. The hook as well as the cable to the sensor were located so as to not interfere with the masticatory process.

The experiment started with the patient being told to open her mouth widely and then bite together. When the masticatory force, thus applied to the sensor, reached a predetermined level of 2N, the first laser pulse was triggered. After a delay of 450 μ s, the second pulse was automatically actuated. The double-exposed hologram was then developed and

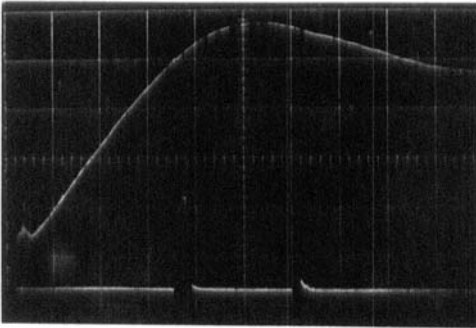


Fig. 9. The force curve (upper) and detector curve (lower) corresponding to hologram P6 on the oscilloscope screen indicate the force variation in relation to the two laser pulses.

Horizontal calibration: 200 $\mu\text{s}/\text{div}$.
Vertical calibration: 0.8 N/div.

fixed. The force increase and the pulses were simultaneously registered on the oscilloscope screen, which was photographed by means of a polaroid camera.

The force increase between the pulses could thus be compared with the hologram evaluation and conclusions could thereby be drawn about deformation and tooth mobility. Owing to the experimental design used the force was fairly well defined as regards point of application, direction, amplitude and duration. The results of one registration (P 6) are shown in Fig. 9 (polaroid picture of the oscilloscope screen) and in Fig. 10 (photographic reconstruction of the hologram).

The direction of forces acting on the sub-miniature force sensor

The simulator tests were carried out so that no tilting or bending movement could occur during the experiment. Since the sensor is positioned between the cusps of the opposing teeth the direction of the resultant force acting on tooth 24 is easily defined as axial to the vertical rod in the sensor.

In the clinical experiments the metal rod was cemented in a well defined position

on to the occlusal surface of tooth 24. If the cusps of the opposing teeth strike the lower surface of the sensor simultaneously during the experiment, the resultant force is axial to the rod.

Any other point of impact gives the same result as long as the sensor remains in the correct position. Mechanically, any force in any direction impacting the lower metal surface can be divided into two vectors. One is parallel to the tooth surface and has no influence on the sensor. The other is perpendicular and causes a resultant force acting on tooth 24 by means of the rod and in its axial direction. The resultant force impacts the tooth and creates a reactive force in the opposite direction. This reactive force actuates the output signal of the sensor. At a predetermined level the first laser pulse is triggered. The increase in force between the pulses during 450 μs depends on the masticatory muscle activity. The type and amplitude of tooth mobility depends for example, on the angle between the rod and the length axis of the tooth. The choice of the magnitude of this angle was made with regard to the aim of the experiment. In the recent development of these experimental methods it was found desirable to have as small a deviation as possible between tooth axis and rod axis. The high measuring sensitivity of the holographic method makes possible the measurement of cusp displacements of 0.5 μm in amplitude.

Error estimation

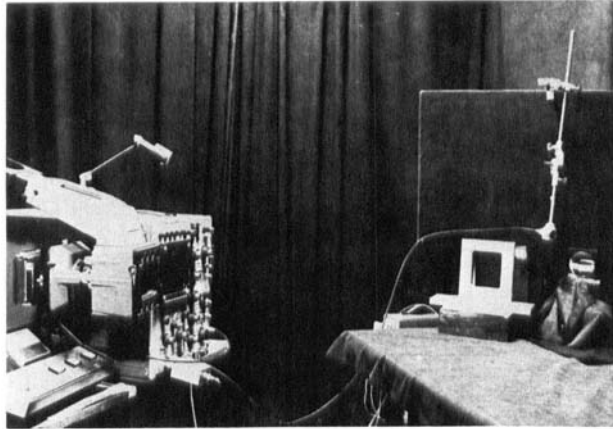
Static evaluation:

Error is caused by practical difficulties in resolving the center of the last fringe.

Static and dynamic evaluation:

Errors are caused by insufficient knowledge of holographic arrangement geometry.

Fig. 10. Arrangement for clinical application. Seen from the left are: remote control station for the laser, oscilloscope with a polaroid camera, eye protection screen, holder for the holographic plate, laser light detector, reference mirror and black curtains which constitute a suitable background for the experiments.



Dynamic evaluation:

Error is also caused by the practical difficulties involved in resolving the center of the first and the last fringe as they move past an object point. This error is inversely proportional to hologram plate dimensions.

Example:

The evaluated absolute displacements (d_a) of P6 have a maximum error (Δd_a) such that:

$$\Delta d_a = \pm (0.1 d_a + 0.3 \mu\text{m})$$

When difference in displacement (d_r) of adjacent teeth is studied the errors of the absolute displacements are compensated and the relative error (Δd_r) is such that:

$$\Delta d_r = \pm (0.1 d_r + 0.3 \mu\text{m})$$

Findings in simulator tests

The optimal positions of the experimental equipment are shown in the hodiogram (Fig. 1).

Distances: Laser head \rightarrow Object 1960—1955 mm
Object \rightarrow Holographic plate 93—100 mm

The pattern of interference fringes was clearly visible in the holograms for a force increase from 2N to 2.5N. The sensitivity and measuring range of the holographic method thus proved to be suitable for

investigations of objects with a size and surface relief like teeth.

The gold paint used for surface preparation prior to holography gave an adequate reflective effect.

Experiments in vivo

The general arrangement for clinical application is shown in Fig. 10. The holograms contain varying patterns of interference fringes depending on force application and angle of exposure. It was possible to perform an evaluation of absolute as well as relative mobility.

Example; Hologram P6 (Fig. 11). The absolute cusp displacement in a plane parallel to the holographic plate was evaluated as $5 \mu\text{m}$ for 23 and 25 and $6 \mu\text{m}$ for 24. Consequently, the relative displacement of 24 in the axial direction was calculated to be $1 \mu\text{m}$. This means that, in this case a force increase of 0.5N has caused an axial translation of $1 \mu\text{m}$. A $2 \mu\text{m}$ simultaneous relative cusp displacement of 24 in the vestibular direction was recorded. During the same moment ($450 \mu\text{s}$) the cusp of 23 was displaced $0.5 \mu\text{m}$ in the vestibular direction. This displacement was probably caused by a



Fig. 11. Photographed holographic reconstruction of the exposed jaw section. The interference fringes indicate the mobility and deformation caused by the force increase between the laser pulses.

force vector acting horizontally in the tight approximation between 23 and 24.

The absolute mobility of the opposing teeth in the holographed jaw section 33, 34, 35, 36 was evaluated as $18 \mu\text{m}$. These cusp displacements were inclined at about 45° in the mesial direction.

DISCUSSION

The aim of this investigation was to develop a non-contact and non-destructive method for studies of the dynamics of human teeth and parodontally anchored prosthodontic appliances during function at low force levels.

Mobility of teeth and deformation of related structures could be recorded with a sensitivity of $0.5 \mu\text{m}$ within a total measuring range of approximately $30 \mu\text{m}$. This method is therefore particularly useful for studies of small force increases and their effects.

The parameters of the experimental equipment were varied in an attempt to optimize the method. The subminiature force sensor could be calibrated for different pulse triggering levels and could be positioned within wide limits during

the experiment depending on the aim of the investigation.

The results of these studies show that this technique can even be applied to rather complicated deformation and mobility processes.

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