Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Surgical Neurology xx (2004) xxx–xxx
SURGICAL NEUROLOGY
www.elsevier.com/locate/surgicalneurology-online

Holographic interferometry of cerebral pulsations☆

Kathryn Ko, MD[a,*], Ronald Erickson, MS[b], Tim Schmidt, BS[b], John Webster, PhD[b,c]

[a]Department of Neurological Surgery, Cornell University, New York, NY, USA
[b]Holographics, Inc., New York, NY, USA
[c]Department of Physics, University of Portsmouth, Portsmouth, Hampshire, UK

Received 26 November 2003; accepted 19 April 2004

Abstract

Background: Holographic interferometry is a noninvasive method used to analyze the mechanical displacement affecting an object undergoing deformation. This techniquehas been primarily applied to inanimate entities owing to the difficulty in producing stress forces in living subjects. In this report, the possibility of harnessing cerebral pulsations as a displacement force to produce interferograms in neurosurgical patients was studied.

Methods: This work evaluates the application of this technology to patients with areas of calvarial loss. Using a pulse ruby laser, holographic interferograms were created in neurosurgical patients with areas of calvarial loss. The cardiac cycle was used to trigger the firing of the laser.

Results: The holographic interferograms were accurate up to within 0.5 mm in outlining the region of bony deficiency.

Conclusion: Holographic interferometry imaging was successfully accomplished using cerebral pulsations as a cyclic displacement-producing force. This method accurately outlined the area of bony loss. A discussion of this technology is included.

Keywords: Calvarial defect; Hologram; Holography; Interferometry; Pulsed laser

1. Objective

A hologram records the wavefront of light reflected from the surface of an object that has been illuminated with a coherent source such as a laser. Reconstruction of that wavefront reveals the object in full 3 dimensions. When an object undergoes displacement or is subjected to deformation after its initial hologram has been recorded, this second image superimposed upon the original hologram produces light and dark fringes or an interference pattern. In other words, a double-exposure hologram of a surface undergoing cyclic out-of-plane movement leads to the formation of a holographic interferogram [3,6,8] from which the behavior of that object under deformation can be studied.

Holographic interferometry applied to medicine has been traditionally used with rigid structures such as prosthetic appliances in dentistry and cadaveric bones including human skulls [1,4,7,9-11]. These objects are coupled to mechanical force–producing devices to introduce structural deformation. Using such studies, the reaction of these materials to the displacement forces could be evaluated. The challenge in applying this technology with patients has been in devising methods of safely producing repetitive strains in living subjects. The current report departs from earlier work with cadavers by harnessing, for the first time, naturally occurring physiologic forces, cerebral pulsations, as a displacement-producing mechanism in neurosurgical patients.

Using cerebral pulsations as a deformational force for interferometric evaluation would normally be impossible because of the overlying skull. Therefore, patients with calvarial defects were studied in consideration of whether the cerebral pulsations can be used to produce holographic interferograms in living subjects and, if so, how accurate

☆ None of the authors have any financial interest in the subject under discussion, nor have they received any financial support for this work.

* Corresponding author. Cherokee Station, P.O. Box 20398, New York, NY 10021-0066, USA. Tel.: +1 866 223 8145; fax: +1 212 988 7211.
E-mail address: k@gyrus.cc (K. Ko).

0090-3019/$ – see front matter © 2004 Published by Elsevier Inc.
doi:10.1016/j.surneu.2004.04.026

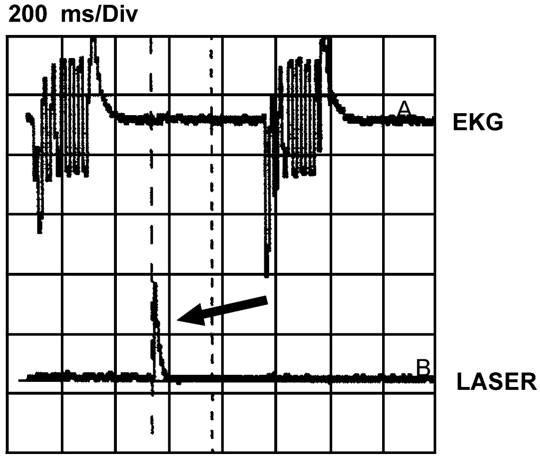

Fig. 1. Oscilloscope trace depicting the double firing of the pulse laser and the patient's electrocardiogram tracing (arrowhead). The double pulse of the laser is seen as one impulse (arrow) because of the greater order of magnitude of the time scale (200 milliseconds per unit) compared with the repetition interval of the laser (800 microseconds).

these interferograms will be in depicting the area of bone loss?

2. Methods

Five patients with cranial vault defects underwent holographic interferometry. Four of whom had a postmissile wound in the head with the initial injury incurring, on the average, 4 months previously and one of whom developed a postoperative infection after tumor removal. All were anticipating cranioplastic procedures that would reestablish each of their calvarial contours. The mean age of the patients was 30 years. The defects were located in the following regions: supraorbital-frontal in 2 patients, temporal-parietal in another 2 patients, and occipital in 1 patient. The widest dimension of the area of bone loss ranged from 2.2 to 7.5 cm. All patients were presumed to have normal intracranial pressure (ICP) at the time of imaging.

2.1. Holographic interferometry

The holographic camera used is a prototype portable pulsed ruby laser system (Holographics, Inc, Long Island, NY), which has a wavelength of 694.3 nm, a pulse duration of 25 nanoseconds, and a power output of 75 mJ. Two pulses are extracted from a single excitation of the ruby crystal. The interpulse width or repetition interval between the 2 pulses of the ruby laser can be set to vary from 300 to 1000 microseconds in multiples of 100 microseconds. The repetitive firing of the laser within this period produces a double-exposed image on a single sheet of holographic film that is the basis for the formation of the interferogram.

The patients were positioned approximately 18 in from the holographic camera to provide an optimal view of the area with bony loss. Standard electrocardiogram electrodes were placed on each patient. A signal from the QRS complex of the cardiac cycle triggers the circuit for the firing of the laser. The trigger circuit introduces a delay of 350 milliseconds before the first pulse of the ruby laser. The electrocardiogram and laser response were recorded on an oscilloscope (ScopeMeter 97, Fluke Manufacturing, Everett, Wash; Fig. 1).

The scalp overlying the regions of bony loss moves in response to the cerebral pulsations between the 2 firings of the laser. The area of the scalp above the intact cranium experiences virtually no displacement because of the dampening effect of the underlying bone. Fig. 2 illustrates the phase relationships for points on a surface illuminated with coherent laser light undergoing displacement (Δd) between time 1 and time 2, as in our patients. At time 1, the surface will contain points A, B, and C, while at time 2, the surface has been displaced such that the new surface points become A', B', and C', respectively. In this instance, the surface has undergone simple displacement toward the observer. The illuminating laser light impinges on the surface at some angle α, and it is reflected toward the viewer at the angle β. The phase shift superimposed between time 1 and time 2, when recorded by holography, will be reflected as interferometric fringe patterns.

Two synchronized images separated in time are exposed on a single filmstrip (Agfa 10E75AH, Agfa, Ridgefield Park, NJ) using a holographic technique, resulting in an interferogram [5,12]. The interferograms are then developed and the patterns evaluated. For the calibration of spatial measurements, a plastic scale in millimeters was included in the field of view of each interferogram. The reconstructed holograms were captured using a high-resolution Megaplus camera (Kodak,

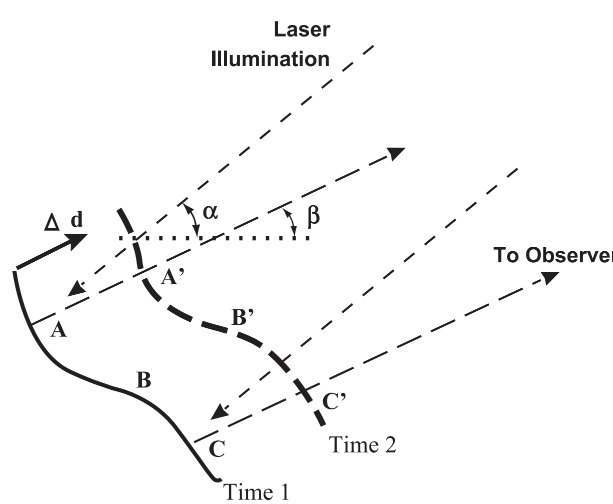

Fig. 2. Schematic diagram of the surface displacement of an object. At time 1, the surface contains points A, B, and C. After undergoing displacement toward the observer at time 2, the new surface points become A', B', and C'. The illuminating laser light impinges on the surface at angle α and is reflected toward the observer at angle β.

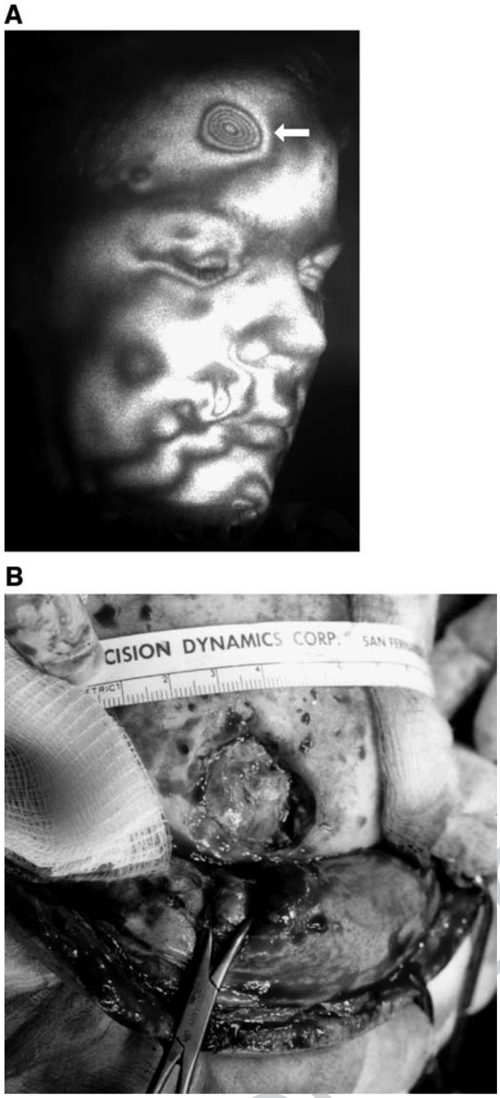

Fig. 3. Holographic interferogram (A) and intraoperative photograph (B) comparing the area of bone loss.

Rochester, NY) and a frame grabber (UPX-2600AT, Univision Technologies, Burlington, Mass). Subsequent image processing on the Tag Image File Format graphic files was performed using a Bioscan software package (Optimas, Bothell, Wash), which includes built-in measurement routines. For example, in Fig. 3A, 3 different operators calibrated linear measurements by manually drawing a cursor line over a marked increment of 1 cm on the plastic scale. Then, the outline of the interferogram was manually traced using a mouse. Bioscan then calculated all relevant measurement values including circumference, major and minor axes, and area. The entire process from patient positioning to completion of the interferometric evaluation averaged 30 minutes.

The measurement data obtained from evaluating the holographic interferogram were compared directly with the actual defect during surgery.

3. Results

The patients experienced no complications during the application of this technology. Four exposures per patient were needed to achieve a completed study that outlined the area of bony deficiency.

3.1. Holographic interferometry

In all studied patients, we found that the cerebral pulsations have sufficient force to result in scalp displacement that can be recorded during holographic interferometric imaging (Figs. 3A and 4A). The QRS wave of the cardiac cycle proved to be a reliable method in triggering the firing of the laser.

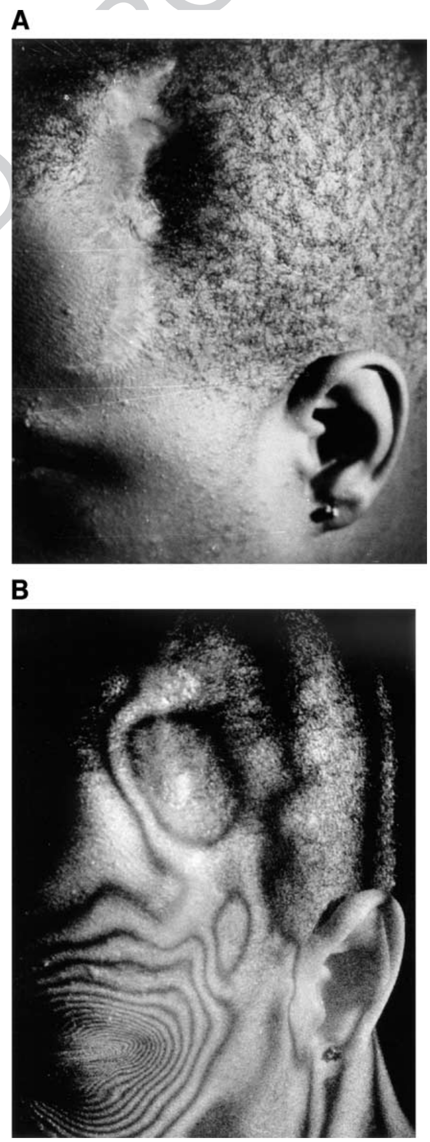

Fig. 4. Photograph (A) and matching holographic interferogram (B) of a patient illustrating the complexity of the fringe pattern surrounding the eye. In contrast, note the absence of fringe patterns on the ear, indicating a lack of any detectable motion by the laser.

All patients underwent satisfactory reconstructive surgery. In patients with cranial vault discontinuities, the resulting interferogram can be interpreted to outline areas of bony loss. The calvarial defect was measured in situ during surgery for a direct comparison with the dimensions and geometry obtained during the preoperative interferometric imaging (Fig. 3A, B). The depiction of the area of bone loss was accurate up to within 0.5 mm of the actual defect as measured in situ at the time of surgery in all patients.

4. Discussion

In the past, interferometric methods have been used to study structural stress and deformation activity in rigid objects such as orthopedic metal implants, teeth, and bones [1,4,7,9-12] as a means of predicting stability and failure. Earlier interferometric efforts in cadaveric human skulls and other bones relied on external appliances such as static loading mechanisms, vibratory transducers, or force-producing devices to generate deformation. Such reports have been of benefit in evaluating the deformational patterns that occur in the isolated human skull upon traumatic impact [1,4,7,10], and these results extrapolated to hypothesize what occurs in the living. These traditional techniques would not be applicable for introducing strain or displacement in patients, and therefore this study's idea of using a physiologically recurring force, cerebral pulsations, to observe deformation is novel.

The mechanical consequences of the cardiac cycle result in the transmission of displacement waves throughout the body. The propagation of the arterial pressure head to the cerebral circulation contributes to the differential pulsations of the brain that are a naturally occurring displacement-producing force. This pulsatile activity is normally obscured from interferometric evaluation because of the cranium. In patients with calvarial loss, we have used this cerebral displacement for producing holographic interferograms that demonstrate boundary because of the immobility of the surrounding intact skull. This is the first report on the successful application of double-pulsed holographic interferometry in human beings using intracranial pulsations as the deformational force.

Holographic interferometry can document extremely small movement over a large field of view [6,8]. The motion may be as microscopic as half the wavelength of the laser light; in this case, displacement of the scalp could be a little as 3.5 μm and still be detectable. Thus, the short wavelength of the laser confers precision to interferometric imaging of greater degree than what we have reported. Other movements including physiologic motion, such as breathing, have no effect on holographic imaging because of the microsecond exposure time. Therefore, holographic interferometry may be a tool for evaluating dynamic physiologic events that escape direct visualization [2,3] and measurement. The potential of this technology can be foretold in Fig. 4A and B. The matching photograph is shown along with the interferogram to orient the reader. The vigorous fringe pattern surrounding the patient's eye indicates that this tissue is undergoing movement (ie, displacement that is detectable with interferometry as a result of the sensitivity inherent in the laser's short wavelength). This movement is not observable with the human eye, nor is it observable with the use of most of the other clinical imaging technologies. In contrast, note the absence of fringe patterns on the ear. The area around the carotid artery on the neck also generates an extremely detailed and complicated fringe pattern. These fringe patterns may reveal information about the status or character of the underlying tissue or organ from where they originate.

The complete analysis of the final interference pattern can furnish more detailed information beyond the outlining of geometry that we have described. The fringes are a quantitative measure of displacement of the subject's surface between the 2 laser exposures and relate to the following equation:

$$\Delta d = n\lambda/(\sin(\alpha) + \sin(\beta))$$

where d indicates displacement; n, number of fringes; λ, wavelength of the laser light; α, angle when the laser light strikes the surface; and β, angle of reflected light toward the viewer [6,8] as depicted in Fig. 2.

Although our findings demonstrate the ability of holographic interferometry to detect biologic displacement related to cerebral pulsations, as applied broadly, this technology is known as a nondestructive-noncontact method of measuring micromovement that does not require surface preparation, does not use a transducer, and is independent of operator technique [13]. Applying the above equation to the resulting interference pattern lends a quantitative meaning to such movement.

Holographic interferometry proved to be an optical method for detecting surface movement in response to the cerebral pulsation cycle. Because cerebral pulsations are related to ICP, holographic interferometry may be advantageous if the interferometric fringe pattern can be found to reflect ICP changes. Because of the sensitivity of this technique, the potential for noninvasively assessing physiologic and pathologic deformation is worth exploring.

5. Summary

Holographic interferograms were produced in patients with cranial bone loss. This study is novel in that a naturally occurring physiologic force, cerebral pulsations, was harnessed as a displacement-producing mechanism. The interferograms accurately outlined the region of bone defect. This technology may have potential as a noninvasive method for assessing an object or organ undergoing micromovement or a strain that is unobservable by other methods.

References

[1] Dorheide J, Hoyer H. Holographic investigation of the impact response of human heads. J Neurosurg 1984;60:718-23.

[2] Hok B, Nilsson K, Bjelkhagen H. Imaging of chest motion due to heart action by means of holographic interferometry. Med Biol Eng Comput 1978;16:363-8.

[3] Hong HD, Fox MD. No touch pulse measurement by optical interferometry. IEEE Trans Biomed Eng 1994;41:1096-9.

[4] Hoyer H, Dorheide J. A study of human head vibrations using time-averaged holography. J Neurosurg 1983;58:729-33.

[5] Ko K, Webster JM. Holographic imaging of human brain preparations—a step toward virtual medicine. Surg Neurol 1995;44:428-32.

[6] Ovryn B. Holographic interferometry. Crit Rev Biomed Eng 1989;16:269-322.

[7] Podbielska H. Mechanical reaction of human skull bones to external load examined by holographic interferometry. Proc SPIE 1986;673:321-6.

[8] Schmidt T, Webster J. Portable holographic interferometry camera detects deterioration in aging aircraft. Sound Vib 1996;6:8-18.

[9] Silvennoinen R, Nygre'n K, Rouvinen J, Petrova V. Bone structure studies with holographic interferometric nondestructive testing and X-ray methods. Opt Eng 1994;33:473-7.

[10] Spetzler RF, Spetzler H. Holographic interferometry applied to the study of the human skull. J Neurosurg 1980;52:825-8.

[11] Vukicevic S, Marusic A, Stavljenic A, Vujicic G, Skavic J, Vukicevic D. Holographic analysis of the human pelvis. Spine 1991;16:209-14.

[12] Webster JM, Schmidt T, Mew JM. A holographic interferometric technique for the detection and computerized recognition of defects in semi monocoque structures. Imaging Sci J 1998;46:11-5.

Commentary

The authors describe the creative application of holographic interferometry to image the human brain. A noninvasive dynamic laser technique is linked to the patient's electrocardiogram to detect brain pulsations through a surgical or traumatic skull defect. Superimposition of 2 serially obtained holograms obtained before and after brain displacement (actually scalp displacement over a cranial defect) during the cardiac cycle produces an image that defines the skull defect through which the brain was studied.

As the authors suggest, the most novel aspect of this work is the use of a natural force (brain pulsations) rather than a man-made one to create movement of the object of interest. The images that result from this project are both captivating and eerie. The authors demonstrate that scalp displacement is an adequate reflection of brain movement through a hole in the skull.

Ko et al fuse the art and science of holography with the art and science of neurosurgery to create a fascinating study. Perhaps, because the subject matter is an unusual read for a neurosurgeon, the technical content would at first seem overwhelming. However, reviewing the material is worth the effort. The most important practical implication of the article is the potential use of the inferred technique for intensive care unit bedside measurements of intracranial pressure and brain compliance in trauma and postoperative patients.

Susan C. Pannullo, MD
Department of Neurological Surgery
New York Presbyterian Hospital
Weill Cornell Medical College
New York, NY 10021, USA