The use of the three-dimensional (3-D) hologram to record and display radiological data has been introduced into the clinical domain. The autostereoscopic property of holography permits the physician to view the patient's entire radiological study interactively on one hologram in full three dimensionality without the need for visual appliances or stereo pairs. By using holograms, the physician's understanding with respect to 3-D form or volume is visually apparent and not based on the mental interpolation of a set of two-dimensional (2-D) slices.

If radiology is as essential to a surgical procedure as the instruments, the radiological hologram, by virtue of its 3-D properties, may be of greater value to surgery because of its proximity to the sterile field. In this way, the surgeon has instant access to these studies and does not have to leave the patient to review films but, instead, can see the holographic radiological view superimposed over the patient. The operation could be performed while the surgeon looks through the holographic image, comparing reality with the radiological view while remaining visually fixed on the patient. Thus the idea of using the superimposed holographic image as an interactive visual map on the operative field during neurosurgical craniofacial procedures was conceived.

In an initial step toward this investigation, computerized tomography scanning–derived narrow band reflection holograms of patients undergoing craniofacial procedures were created to evaluate the applicability of superimposing these three-dimensional images (3-D) on the operative field during neurological surgery. These sterilized radiological holograms were positioned over the surgical site by using bone sutures as registration points between the skull and the 3-D image to serve as a visual template between the patient and surgeon. Surgeries were then performed with the surgeon looking through the radiological hologram at the patient. Holograms were accurate to within 2 mm (plus or minus) of the actual calvarial anatomy. The use of the holographic image as a visual guide during surgery eliminated intraoperative guesswork or free-handed contouring. To the author’s knowledge, this is the first report of the superimposed holographic image used in situ during surgery.

**Methods**

**Patient Selection**

The study was limited to patients in whom procedures were performed that solely involved the calvaria so that the hologram need only contain the 3-D image of bone. This avoided the extra steps required in creating multiple holograms of both bone and subdural anatomy, which would have been mandatory had patients with intracerebral lesions been included.

Holograms were made for three patients undergoing craniofacial surgery. Two patients had sustained previous cranial trauma caused by a gunshot wound and required secondary calvarial repair procedures. The third and most recent patient, an infant with Crouzon’s syndrome, required a procedure that included orbital advancement for coronal synostosis. No patient underwent any radiological imaging or additional exposure for the sole purpose of acquiring holographic images. In each case, the holograms were used during the preoperative conference for patient education, and comments were recorded. The holograms were placed over the area of concern during the office visit in a preoperative simulation. This allowed a final check of the hologram against the actual anatomy prior to sterilization.

**Technical note**

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Computerized tomography scanning–derived narrow band reflection holograms of patients undergoing craniofacial procedures were created to evaluate the applicability of superimposing these three-dimensional images (3-D) on the operative field during neurological surgery. These sterilized radiological holograms were positioned over the surgical site by using bone sutures as registration points between the skull and the 3-D image to serve as a visual template between the patient and surgeon. Surgeries were then performed with the surgeon looking through the radiological hologram at the patient. Holograms were accurate to within 2 mm (plus or minus) of the actual calvarial anatomy. The use of the holographic image as a visual guide during surgery eliminated intraoperative guesswork or free-handed contouring. To the author’s knowledge, this is the first report of the superimposed holographic image used in situ during surgery.

**KEY WORDS** • hologram • holography • frameless stereotaxis • craniofacial surgery
Patients underwent CT scanning (GE Hi Speed Advantage CT; General Electric Medical Systems, Waukesha, WI; and Elscint CT-Twin; Elscint, Hackensack, NJ) according to the normal CT acquisition protocol. As experience was gained, the radiological profile evolved to enhance the final resolution of the holographic image; therefore, each of the patients underwent slightly differing data-capture sequences.

In the two patients who had suffered trauma, the preoperative radiology or data set was based on routine protocols. These studies were ordered on a 512 matrix and were not specified for reformatting, as was routine at our institution for posttrauma patients at that time. The hologram was then constructed from this existing radiological set.

In the first trauma case, the CT scan consisted of seven slices obtained at 1.5-mm intervals through the area of bone loss and 14 slices at 5-mm intervals in the regions outside the defect. With this information, the bone-data outline was rendered into a hologram.

In the second trauma case, the slice interval was 5 mm with a 2.5-mm interpolation over the area of the calvarial defect. This hologram was created based on surface mapping of over 24 slices from these data (Fig. 1).

In the first two cases, the CT diameter of the field of view (DFOV) was 22 cm with a 512 data matrix. The linear resolution of the axial data was submillimeter (220/512 = 0.43 mm). Because in the first case the slice interval through the area of the defect was 1.5 mm, the longitudinal resolution (z-axis) was limited to the 1.5-mm slice thickness. In the second case, the resampling interpolation at 2.5 mm provided a longitudinal resolution limit of 2.5 mm.

Based on what was learned in the earlier cases, the radiological study was specified for reformatting from a spiral Elscint CT system in the most recent case, the patient with Crouzon’s syndrome. This yielded highly resolved radiological images for the hologram at no additional exposure to the patient. The helical CT scanning captured a 20-cm DFOV with a 1024 data matrix that was reformatted to a surface map. The axial resolution from the 1024 matrix was 0.2 mm (200/1024). With the slice interval for the helical format set at 2 mm, the longitudinal resolution limit was 2 mm.

Creation of the Hologram

The degree from normal at which the surgeon’s halogen headlamp will strike the holographic carrier during the operation had to be anticipated prior to generation of the hologram to ensure the correct illumination of the image with the surgical headlamp. The final holographic form was thus configured to anticipate the patient’s intraoperative position on the operating table so that the image would coincide with the actual anatomy.

A large number of radiological views derived from the CT data representing cranial volume were incorporated within each hologram. In other words, more than 24 2-D slices were consolidated in a single 3-D holographic image. The actual hologram was registered by means of a continuous-wave 100-mW helium–neon laser with an exposure time of 20 seconds at a 633-nm wavelength by using standard holographic principles specified in an earlier article. The hologram was recorded on transparent triacetate film (20 × 25 cm, 8E75HD; AGFA, Ridgefield Park, NJ) and was laminated to a Plexiglas carrier. The optics of the camera were adapted to produce a hologram that yielded approximately 10 cm of working space between the holographic carrier and the skull, allowing room for the surgeon’s hands to maneuver. Specifically, the holographic camera was adjusted to place the image at a depth of field of 10 cm. The image was configured to hover beneath the carrier, superimposed over the skull, in one-to-one alignment with the bone structures of the patient beneath it.

In one of these cases a second series of holographic images was created to demonstrate viewing of the “repaired” skull anatomy. In this case one hologram was made of the cranium with the skull defect present and another hologram was made with the skull defect corrected, so that the contour of the skull was normalized. The “repaired” hologram, which simulated an idealized postoperative result, was used to guide the final 3-D conformation during surgery.

Initially, as many as 24 hours of bench work per holo-
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The holograms were committed from the beginning of CT data reformation to lamination of the holographic film on the Plexiglas carrier (thickness 3 mm). By the third case, however, this process had shortened by almost half.

Preliminary investigation showed that the holographic emulsion was stable after gas sterilization and the process did not degrade the image. All holograms were gas-sterilized in preparation for intraoperative use.

Preoperative Rehearsal and Holographic Image–Guided Surgery

In the two cases of calvarial defects, the repair construction (titanium mesh) was configured based on the 3-D image and repair simulations and rehearsals were done on the holograms prior to the actual operation.

After preparation of the surgical field by reflection of the scalp flap and exposure of the cranial vault, the hologram was secured over the operative field in register with the bone landmarks (Fig. 1) and illuminated with the surgeon’s halogen headlamp while the overhead lights in the operating room remained on. The hologram was then used as a visual reference to assist in the implantation of the prefabricated construct and reshaping of the calvaria. Because of its transparency, the surgeon was able to look through the hologram superimposed on the skull, using the 3-D image as a template for guiding surgery. In the case of the prerepaired holographic image, the contour of the calvarial reconstruction was matched to the hologram.

Results

Patient Participation

There were no complaints from, or complications in, the patients as a result of using the holograms during surgery. The holograms allowed preoperative rehearsal of the surgical procedure both in the laboratory and in the office. The accuracy of the 3-D image position and viewing angle with respect to the patient’s pathological characteristics was checked in the office, leading to a higher confidence level in the use of this technology during the surgical procedure. All patients and their families preferred having their own hologram used as the visual educational aid over the sheet of cross-sectional scan slices during explanation of the procedure.

Holographic Image and Preoperative Rehearsal

The routine CT protocol used for preoperative study of these cases was of sufficient detail to allow for the creation of these holograms and no further radiological data were necessary. Presurgical examination of the CT hologram allowed the full volume of the skull defect to be studied and understood. The holograms matched to within a mean of 2 mm (plus or minus) of the calvarial defect in patients who had suffered trauma. In the patient with Crouzon’s syndrome, the positioning of the hologram and patient was initially mismatched by 5° in the z–y plane and was subsequently realigned during the operation procedure by altering the patient’s position (Fig. 2). None of the images had distortions or deletions of information and all yielded 30 to 40° of horizontal parallax viewing. It was not necessary to examine the 2-D scan slices on the viewbox in the operating room during any of the procedures.

Discussion

During CT and magnetic resonance (MR) imaging, the acquired data points represent the patient’s volumetric anatomy. Even though all the information pertaining to a patient’s 3-D structure resides in the computer’s memory, this knowledge is underused clinically because there is no
technique in routine use that can present these data to the physician in a manner that portrays true volume. Current radiological images, although detailed and of high resolution, can be reconstructed to simulate three dimensionality with computer adjustments such as lighting and shading; however, they are still only 2-D. Therefore the “reading” of volume remains subject to the critical judgment of the surgeon based on experience extrapolating from 2-D imaging studies. Clinicians must learn to picture spatial relationships in their minds and, therefore, physician cognition still plays a major role in the translation of these cross-sectional imaging slices into living 3-D anatomy.

One potential technique of representing biomedical data in three dimensions is holography. Holography is a departure from stereoviewing in that the image is autostereoscopic and 3-D without the need of stereo pairs or visual appliances. Holograms present multiple digital data sets in a unified volumetric and interactive format.

The intent of this preliminary study was to show that a hologram created from standard, preoperative radiological images would have possible clinical advantages for both the patient and surgeon. Furthermore, this image could be brought onto the operative field and superimposed in anatomical register with the cranium during surgery. Finally, the operation could be performed with the surgeon looking through the image and its presence would be visually helpful during the procedure. To my knowledge, this is the first report of holograms being used in the operative field and of neurological surgery being performed with the aid of an in situ 3-D superimposed image.

These holograms illustrated pathological characteristics of the calvaria in sufficient detail to be of clinical relevance during both the planning and the undertaking of the operation. The clarity of these images is due to the fact that there is no loss of resolution in the radiological image during conversion of the data to a hologram. The resolution of a radiological hologram is limited by the resolving power of the digital data from which it is derived. The image resolution of a hologram can be on the order of 25 μm, and the narrow band reflection holograms produced here have a resolution of 250 μm. In other words, holographic image resolution is an order of magnitude greater than the current CT or MR imaging digital data. Therefore the CT matrix (512 × 512 pixels or 1024 × 1024 pixels) of data points imposes the resolution limit on the image and not the holographic technology. Contemporary scanning techniques have not yet reached the potential resolution of the hologram.

All patients exposed to the holograms noted that the images strengthened their understanding of the procedure to come. Radiological holograms grant the surgeon the opportunity to rehearse the procedure prior to incision and, in two cases of trauma, the actual cranioplastic construct was fashioned directly from the hologram, requiring only minor adjustments during the actual surgery. The benefit of rehearsing the surgery by interacting with the hologram could also shorten the actual procedure. This may enhance confidence in the upcoming procedure in both the surgeon and patient. However, at this stage, preparation of these holograms is entirely manual and requires a lengthy process, offsetting the time advantage gained in the operating room.

The surgeon’s halogen headlamp proved to be an ideal illumination source for the visualization of the superimposed hologram without moving the line of sight away from the patient or dimming the overhead operating room lights. Two or more surgeons may view the holograms because each has its own light source, that is, the headlamp. Because of parallax the holographic image is interactive with the viewer. Thirty to 40 degrees of horizontal parallax are available for viewing in these cases without image distortion at the limits. As the surgeon shifts position, the holographic image changes to reflect the new viewpoint. This interactivity is critical during surgery and permits surgeons to vary their perspective on the operation concurrently with the image while leaving their eyes fixed on the patient. The hologram is easily assimilated into the operating field and procedure. No new skills are required in the reading of a hologram at the office or during its use in surgery. The in vivo use of holography opens the door to the interactive use of radiology on the sterile field over the patient.

The hologram illustrating the repaired calvaria confirmed the use of the holographic image as a visual guide during surgery. It is anticipated that with the superimposed hologram, artistic judgment of symmetry and/or form on the field may be rendered less critical. Calvarial readjustment is not done freehand, but is guided by the life-sized superimposed holographic contour, assuring an aesthetic result. In the present cases, this eliminated time-consuming adjustments and visual guesswork, especially in the case of the patient with Crouzon’s syndrome. In this case, although the image was initially mismatched in the z-y plane, an alteration in the patient’s position corrected the image misalignment, demonstrating the flexibility inherent in working with an interactive image. Bandeau advancement and fixation were assisted by the hologram. In this limited study, the hologram provided an accurate visual reference and guide for calvarial reconstruction using bone landmarks as registration points.

There is no doubt that the next improvement in visualization will be in areas that depict true three dimensionality. Three-dimensional medical images will interact with the physician and ideally be superimposed and positioned closer to the patient than a view box on the wall. The radiological hologram may be of the greatest use to the clinician, who requests the radiological image, and of less use to the radiologist, who is trained in the cognitive shift of two dimensions into three. Holography, however embryonic its development, may ultimately find a role in craniofacial neurosurgery if the technical constraints of its physics can be conquered. With this may follow potential uses in frameless noncontact stereotaxy with multimodality layering of holograms. Holography is not so much a jump into the third dimension, but a logical step along the progressive continuum of representing the human body: from drawing to photography, to x-ray studies, to CT and MR imagining in two dimensions, and finally in three dimensions.

Conclusions

Radiological data are as important to the operation as the surgical instruments and should reside close to the patient within the sterile field so that surgeons do not have
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to shift their eyes to examine the imaging while operating. Three-dimensional holograms may prove to have clinical benefit in preoperative planning or rehearsal. During the actual surgery, when superimposed on the patient during craniofacial reorganization procedures, the holograms may aid the surgeon to attain an enhanced aesthetic result in a shorter time. In the present cases the use of intraoperative interactive 3-D holographic images proved useful. However, enthusiasm for the process must be tempered by the knowledge that, at present, this technology is labor intensive and expensive.

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References


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