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The Applicability of Holography in Forensic Identification: A Fusion of the Traditional Optical Technique and Digital Technique*

ABSTRACT: In this study, the applicability of holography in the 3-dimensional recording of forensic objects such as skulls and mandibulae, and the accuracy of the reconstructed 3-D images, were examined. The virtual holographic image, which records the 3-dimensional data of the original object, is visually observed on the other side of the holographic plate, and reproduces the 3-dimensional shape of the object well. Another type of holographic image, the real image, is focused on a frosted glass screen, and cross-sectional images of the object can be observed. When measuring the distances between anatomical reference points using an image-processing software, the average deviations in the holographic images as compared to the actual objects were less than 0.1 mm. Therefore, holography could be useful as a 3-dimensional recording method of forensic objects. Two superimposition systems using holographic images were examined. In the 2D–3D system, the transparent virtual holographic image of an object is directly superimposed onto the digitized photograph of the same object on the LCD monitor. On the other hand, in the video system, the holographic image captured by the CCD camera is superimposed onto the digitized photographic image using a personal computer. We found that the discrepancy between the outlines of the superimposed holographic and photographic dental images using the video system was smaller than that using the 2D–3D system. Holography seemed to perform comparably to the computer graphic system; however, a fusion with the digital technique would expand the utility of holography in superimposition.

KEYWORDS: forensic sciences, personal identification, superimposition, holography, photography, dentition, anthropometry

The identification of skeletonized remains is one of the most important tasks in forensic investigation. There are three main methods of superimposition using the skull and ante-mortem facial photographs of potential candidates: (1) the photographic, (2) video-assisted, and (3) computer graphics methods. The photographic and video-assisted methods can be employed as long as the skull is preserved and real-time matching is possible. On the other hand, the computer graphics method is able to preserve the 3-dimensional shapes of the skull and dentition for future use. It is useful to record and save 3-dimensional images of the remains, especially when there are no candidates.

Holography (4,5) is known to be a good 3-dimesional recording technique. Two types of images, real and virtual, can be obtained from a holographically exposed film, or hologram. A hologram records the interference fringes produced by the reinforcement or cancellation of the light waves of two different intersecting laser beams: a laser beam reflected from the object onto the film and a laser beam (the reference beam) hitting the film directly. When the reference beam is again pointed at the hologram, the image of the original object appears in the space where the original object had been. In the field of dentistry, some attempts were made to preserve the images of denture molds by holography during the 1970s and 1980s (6,7). Virtual images of study models were utilized by orthodontists to analyze tooth movement (8–10). Harradine (7), however, reported that the hologram cannot be a substitute for the clinical orthodontic study model and should be made available for laboratory use instead. Recent studies have shown that stress analyses of skulls and the recording of the dimensional changes in impression materials are possible using holographic interferometry (11,12). On the other hand, holography has been utilized in the early days of medical diagnostic imaging (13,14). Recently, 3-D volumetric holography, which can reconstruct a 3-D image from about 40 CT images, was reported (15,16).

In forensic investigation, holography was applied by Evett (17), who tested the possibility of using holography to decipher impressions into paper. In the present study, the accuracy of holographic 3-D images of forensic objects and their possible use in forensic superimposition using digital techniques were investigated.

Materials and Methods

Specimens

A skull (adult, male), which had been preserved at the Department of Anatomy, Iwate Medical University School of Medicine, was used as the object. Six study models, which were taken from adult volunteers (2 male and 1 female maxillas, and 1 male and 2 female mandibulae), and a skeletonized mandibula (adult, male) were also employed as objects.

The dentitions of the mandibular bone and the 6 study models were photographed at a distance of 2 m by a digital camera (Olympus C-4040 Zoom, Japan) as comparative images for superimposition. An X-ray of the anterior teeth of one of the volunteers was also taken.

Holographic Recording

A double-beam reflection holography system (5) was used in this study (Fig. 1). Light-sensitive film coated with silver salts

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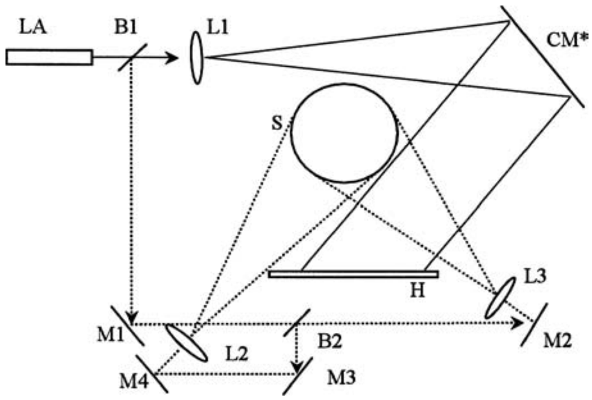

FIG. 1—*The optical system for recording. LA: Laser; B1, B2: Beam splitter; L1–L3: Lens; M1–M4: Mirror; H: Holographic film; S: Sample stage; CM: concave mirror.*
* *A flat mirror is used instead of the CM in recording the skull.*

(PFG-01–45, PFG-01–3040, Chuou Seiki, Japan) was used as holographic film. The recording conditions are shown in Table 1. A monochromatic light beam from a helium-neon laser (GLG5410, 10 mW, 632.8 nm, Showa Optoronics, Japan) was split by the beam splitter. One beam (the reference beam) was expanded through the lens and collimated with the concave mirror, after which it hit the holographic film directly. The other was expanded by two lenses, and hit the object. The reference beam hitting to the plate directly and the beam reflected from surface of the object onto the plate underwent mutual interference. The interference fringes were recorded on the light-sensitive film, resulting in a hologram. The exposed film was immediately developed with a developer kit (Kodak P–71), immersed in fixing and bleaching solutions, and dried.

Reconstruction of the Holographic Images

The virtual holographic image appears on the other side of the holographic plate by exposure to the same reference light, whereas the real image appears on the viewer's side of the holographic plate (Fig. 2). The virtual image can be observed by human eye with full parallax. The real image was can be visualized by projecting it onto a frosted glass screen.

Observable Angles of the Virtual Images

The horizontal and vertical angles of the skull image observed in the hologram were examined on the basis of the Ohr-Augen-Ebene (OAE) and the median plane. The teeth of the mandibular bone and the study model images were examined on the basis of the occlusal surface of the teeth (OST).

Accuracy of the Reconstructed Images

3-dimensional superimposition of the virtual images and the original objects—Each virtual image was superimposed 3-dimensionally onto the original objects placed at the position of initial recording.

Comparison using anatomic measurements—A digital micrometer caliper (Code No. 500-302, 0.01–200 mm, Mitsutoyo Co., Japan) was used to measure the distances between the following anatomical reference points: nasion-gnathion (n-gn), gonion-gonion (go-go), zygomaxilla-zygomaxilla (zy-zy) of the skull, and the distal margins of the right and left homonymous teeth of the mandibula and the 6 study models. The distances in the real images were directly measured on the frosted glass with the digital micrometer caliper.

For the measurement of the virtual images, double-exposure holograms of the original objects and 3-dimensional scales were prepared. The virtual images appeared on the other side of the hologram, and in order to avoid the inaccuracy of measurement in 3-D space, a comparison was made using 2-D digitized images taken from various angles through the holograms. The distances between the anatomical reference points in the virtual images were estimated as follows: Virtual holographic images and photographs of the original objects were taken by digital still camera, saved on the hard disk of a personal computer (PC), and imported into Adobe Photoshop (Adobe) image processing software. The scale factor of the virtual image was calculated using the scale tool of Photoshop and the markings of the 3-dimensional scales on the

TABLE 1—*Shooting condition in holography.*

Subject	Numbers	Light-Sensitive Material: Size (mm)	Plate	Code No.
Skull	1	300 × 400	Glass	PFG-01–3040
Mandibula	1	101 × 127	Glass	PFG-01–45
Study model (maxillary)	3	101 × 127	Glass	PFG-01–45
Study model (mandibular)	3	101 × 127	Glass	PFG-01–45
Study model (maxillary)	1	101 × 127	Glass	PFG-01–45

Subject	Numbers	Shooting: Direction	Distance (cm)	Exposure Time (s)	Reference Light
Skull	1	Vertical to GHP*	17	120	diffused‡
Mandibula	1	Vertical to OST†	5	8.5	parallel
Study model (maxillary)	3	Vertical to OST	5	8.5	parallel
Study model (mandibular)	3	Vertical to OST	5	8.5	parallel
Study model (maxillary)	1	Lateral 45° angle to arch length	5	8.5	parallel

* German horizontal plane, † Occlusal surface of teeth.
‡ Because the skull is as big as the subject, parallel light in the optical system could not be prepared.

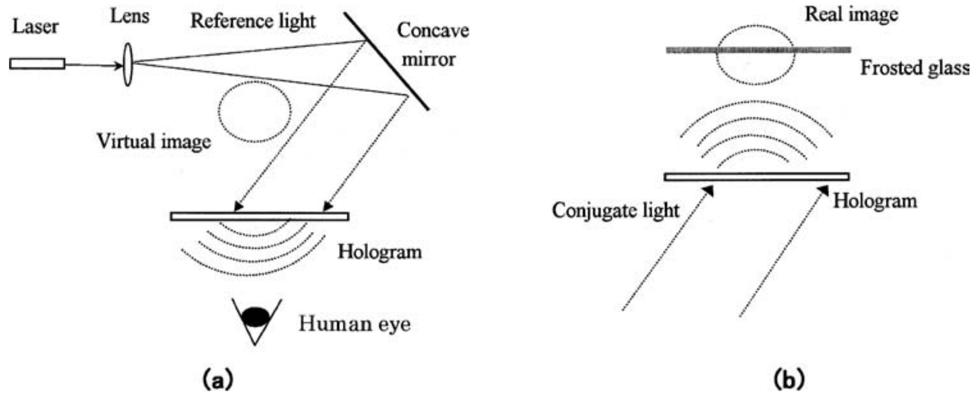

FIG. 2—*The reconstruction of the virtual image (a) and the real image (b). The virtual image appeared beyond the hologram upon exposure to the reference light. The real image appeared upon exposure to the conjugate light, which was pointed toward the hologram in a direction opposite that of the reference light, and was focused on a frosted glass screen.*

double-exposed hologram. Each distance between the anatomical reference points was measured ten times, and the accuracy of reconstruction was estimated in terms of the average, standard deviation (SD), and standard deviation of the mean (SDOM).

Superimposition of the 2-D Image

2D–3D superimposition—The dentitions of the models were assumed to be those of actual maxillae and mandibulae. Their virtual images were used for superimposition on dental photographic images. Figure 6 shows the 2D–3D superimposition system. The hologram was placed in front of a color LCD monitor (Sharp LL-M1550A, Japan) connected to the PC. After the 2-D dental image taken by the digital still camera was imported into Adobe Photoshop, the virtual holographic dental image was projected between the monitor and the hologram. In order to superimpose the 2-D dental image on the monitor onto the holographic virtual image, the size of the 2-D dental image was adjusted to match the virtual image using Photoshop. The aspect of the holographic virtual image was matched with the 2-D image on the LCD by changing the observation angles of the camera. The superimposed image was taken by the digital camera, which was connected to the monitor, and saved.

Video superimposition-Superimposition was done between the video image of the holographic virtual image and the 2-D digitized image of the original object. The video superimposition system consists of a monochrome CCD camera (FCD-10, Ikegami, Japan) with a 50 mm lens (Nikon, F1.4, Japan), a PC running the Rugle software (Medic Engineering, Japan), which is specifically designed for superimposition, and a color LCD monitor. This set-up was originally designed for craniofacial superimposition (18). The hologram was placed at a distance of 2.5 meters from the CCD camera in order to obviate perspective aberration. The virtual holographic dental image taken with the CCD camera was imported into the software program, and superimposed onto the 2-D dental image, which had been fed into the software (Fig. 9). The software can fade images in/out, and perform wipeouts in the vertical and horizontal directions. The two images were superimposed on the monitor using these functions.

Evaluation of matching—Both in the 2D–3D and the video superimposition method, the outlines of the six teeth from the right to the left canine of the 2-D mandibular bone image and virtual holographic image were superimposed. The average values of the normal distances between the outlines of the images were calculated by the Rugle software (19).

Results

Reconstruction of the Holographic Image

All of the virtual holographic images of the skull, the 6 study models and skeletonized mandibula could be reconstructed 3-dimensionally in the same position where the objects were located at the time of the recording. The reconstructed images had transparency. Although slight speckle noise due to the laser beam appeared, details of the reconstructed images could be observed through the holograms (Figs. 3, 4). On the other hand, the real holographic images, which were focused on a frosted glass screen, appeared as the cross-sectional images of the objects, and the cross-section in focus could be changed by moving the screen backward and forward (Fig. 5).

Observable Angles of Objects in Virtual Images

The observable angles according to the anatomical plane are shown in Table 2. The angle depends on the size of the holographic plate and the object recorded. The smaller the object, the larger the observable angle.

Accuracy of the Reconstructed Images

The 3-dimensional superimpositions of the virtual holographic images and their original objects were successful. The distances between the anatomical reference points on the virtual images were almost identical to those on the objects (Table 3). The reconstruction of the dentition was also successful. The average deviation of the distances between homonymous teeth were 0.0 to 0.11 mm between the objects and their images (Table 4). No significant differences could be recognized between the deviations in the measurement of the anterior and posterior teeth. Similar results were obtained in the reconstruction of the 6 study models.

Superimposition of the 2-D Image

2D–3D superimposition—When superimposing the photograph of the anterior dentition of the study model onto the virtual image using the 2-D–3-D superimposition system, the buccal outlines (the incisal margins, the mesial and distal edges of each incisor) were successfully matched. However, a slight discrepancy was observed in the outlines of the right and left canines (Fig. 7). The virtual holographic image of the model taken from an angle of 45° was effective in the superimposition onto the dental photographic image in profile (Fig. 8).

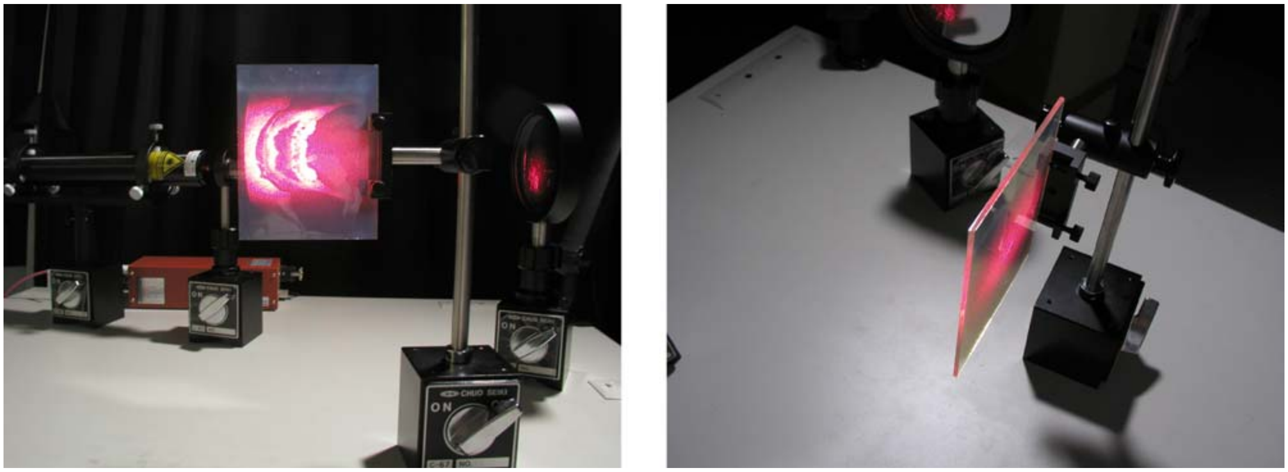

FIG. 3—*The virtual image of the skeletonized mandibule. The image was observed through the hologram (left). There is nothing behind the hologram (right).*

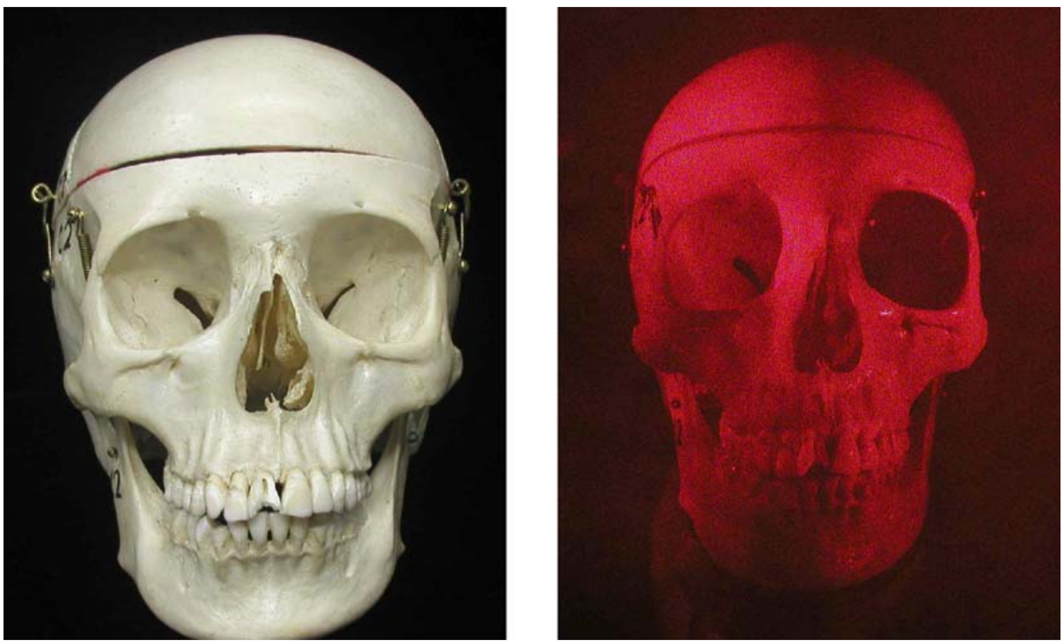

FIG. 4—*The skull (left) and its virtual image (right).*

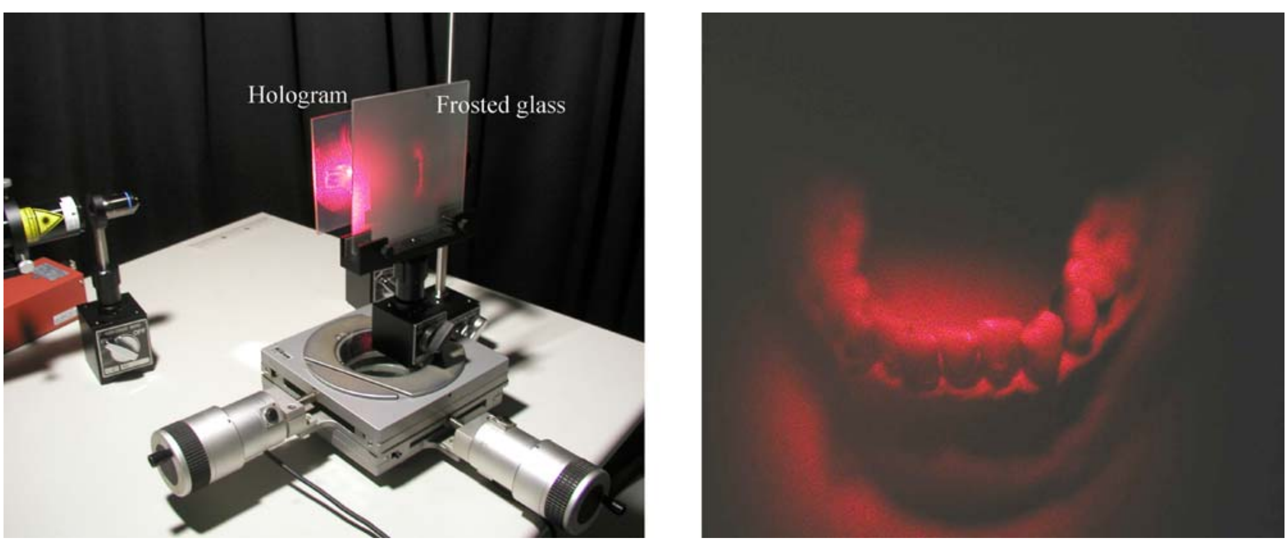

FIG. 5—*The projection of the real image. A frosted glass screen on an x-y stage was placed in front of the hologram (left). The image was frontal sectional, and the cross-sectional image changed with the backward/forward movement of the frosted glass screen.*

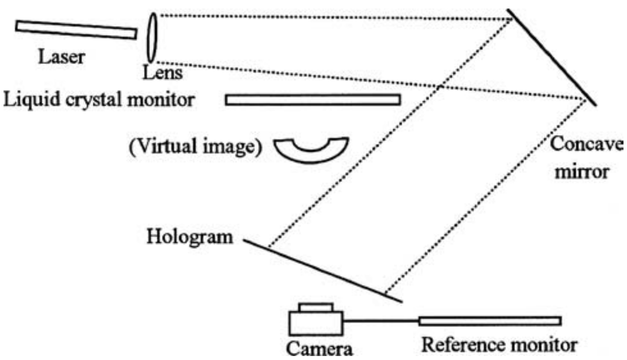

FIG. 6—*2D–3D superimposition system. The virtual image beyond the hologram was visually superimposed onto a 2D image on the LCD monitor.*

TABLE 2A—*Observable horizontal angles in virtual images.*

Virtual Image	Numbers	Standard Landmark	Above	Below
Skull	1	GHP*	30°	35°
Teeth of skull	1	OST†	60°	25°
Teeth of mandibulae	1	OST	60°	25°
Teeth of maxillary model	3	OST	10–15°	22–25°
Teeth of mandibular model	3	OST	20–25°	10–11°

* German horizontal plane, † Occlusal surface of teeth.

TABLE 2B—*Observable vertical angles in virtual images.*

Virtual Image	Numbers	Standard Landmark	Left	Right
Skull	1	Median Plane	25°	24°
Teeth of skull	1	OST*	45°	43°
Teeth of mandibulae	1	OST	12°	12°
Teeth of maxillary model	3	OST	10–11°	9–10°
Teeth of mandibular model	3	OST	12–14°	10–14°

* Occlusal surface of teeth.

TABLE 3—*Errors between anatomical landmark measurements of the skull and those of its virtual image.*

	Skull			Virtual Image			
Landmark	Average*	SD	SDOM	Average*	SD	SDOM	Error
n-gy	104.48	0.16	0.07	104.48	0.08	0.03	0
zy-zy	112.85	0.14	0.06	112.87	0.13	0.06	0.02
go-go	84.18	0.02	0.01	84.08	0.09	0.04	0.1

* Measured ten times. Units: mm.

Video superimposition—The buccal outlines of the dentitions of the virtual holographic image captured by the CCD camera and the photograph of the mandibular bone were well matched by the video system using the fade in/out and wiping functions of the Rugle software (Fig. 9).

Evaluation of the matching—The operation screen on which the normal distances between the outlines of the teeth images were measured is shown in Fig. 10. The average distances of the teeth outlines between the 2-D image and the virtual holographic image for each superimposition system are summarized in Table 5. The

TABLE 4—*Error between the distances of distal margins of the right and left homonymous teeth of the mandibula and those of its reconstruction images.*

Corona Dents	1	2	3	4	5	6	7	Average Error
Mandibula	11.62	20.31	26.52	33.76	34.26	35.38	41.3	
Virtual image	11.68	20.32	26.63	33.72	34.25	35.39	41.39	
Error	0.06	0.01	0.11	0.04	0.01	0.01	0.06	0.04
Real image	11.59	20.36	26.49	33.74	34.22	35.38	41.41	
Error	0.03	0.05	0.03	0.03	0.04	0	0.08	0.04

Each distance of corona dents is the average value of ten measurements. Units: mm.

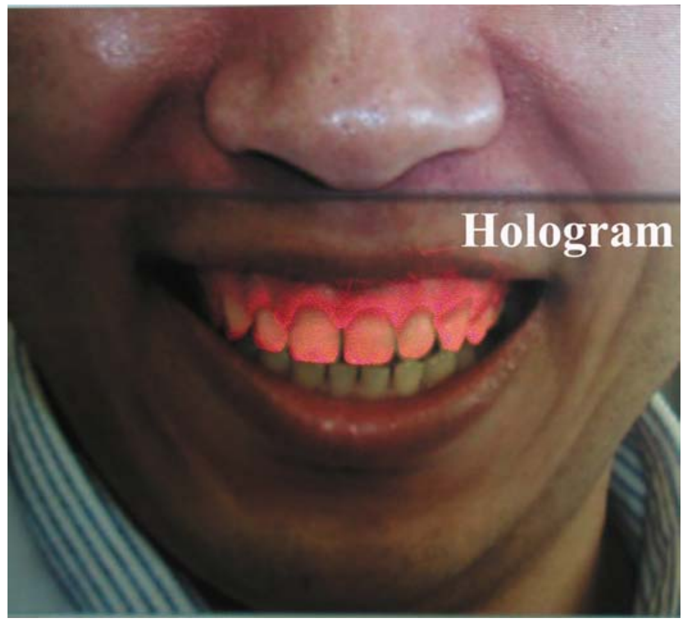

FIG. 7—*Superimposition of the virtual image onto the photograph of the anterior dentition of the subject, using the 2D–3D system.*

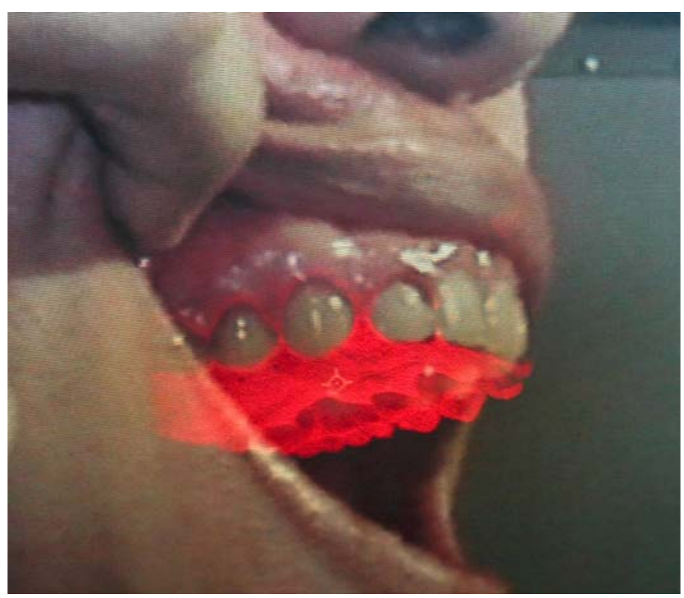

FIG. 8—*Superimposition of the virtual image of a hologram of the model recorded from the right at an angle of 45° onto the 2-D photograph of the subject shot from the right at an angle of 60°, using 2D–3D system.*

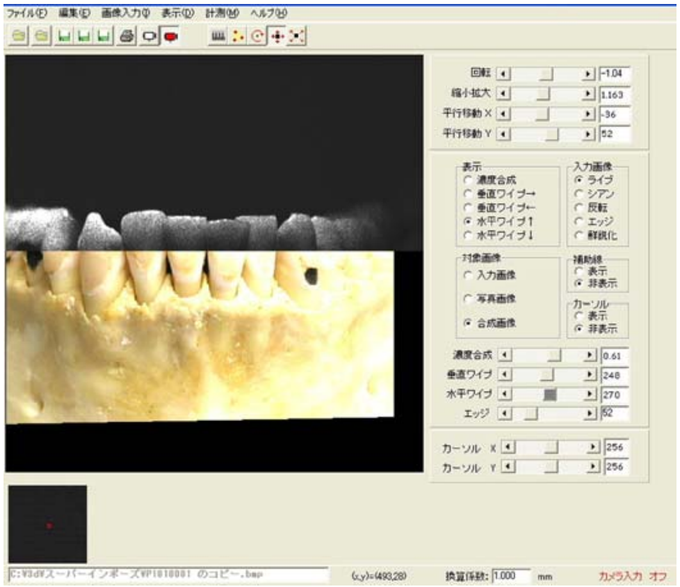

FIG. 9—*The operation screen of the video superimposition. The holographic image inputted through the digital camera and the 2-D image of the mandibula were superimposed on the screen. Functions for wiping, fade in/out, etc. were applied on the right side.*

discrepancy of the video system was smaller than that of the 2D–3D system, especially for the posterior teeth.

Discussion

The anatomical comparison between the skull and facial photographs of the candidate is known as the most conventional method for identifying remains. Video superimposition (2) and computer-assisted (19,20) methods are designed for real-time matching. The computer graphic method (3,21) may come to be used effectively in the future; however, some problems remain regarding the 3-dimensional recording of forensic objects. For example, laser-scanning devices are unsuited for processing 3-D data of lustrous, blackened or odd-shaped objects. 3-D images reconstructed by these devices are, in general, not free of distortion, and require a large amount of storage space for saving and manipulating the data.

In Japan, unidentified remains, including skeletonized ones, stay in the custody of an administrative institution and are eventually cremated unless the victim is presumed to be implicated in criminal violence. Thus, for future superimposition in cases where candidates do appear at last, it seems essential that the skull and dentition should be recorded and saved as 3-dimensional images in addition to 2-dimensional ones.

Holography is known as a unique optical technique capable of recording the 3-D data of an object. In this study, we verified how close the holographic images of forensic objects are to reality. In addition to evaluating the holograms by visually superimposing them onto the actual object, quantitative evaluation was carried out using image-processing software. The results showed that the discrepancies in the anatomical measurements between the reconstructed images and the original objects are very small (Tables 3, 4). Holography is considered as a kind of photographic technique, but the recording is carried out without a camera lens, and the light reflected by the object directly reaches the film. Consequently, it is plausible to assume that holographic images have little distortion. The discrepancies shown in Tables 3 and 4 might be classified as systematic errors rather than random ones. The results suggest that the virtual images produced by holography could be useful as a

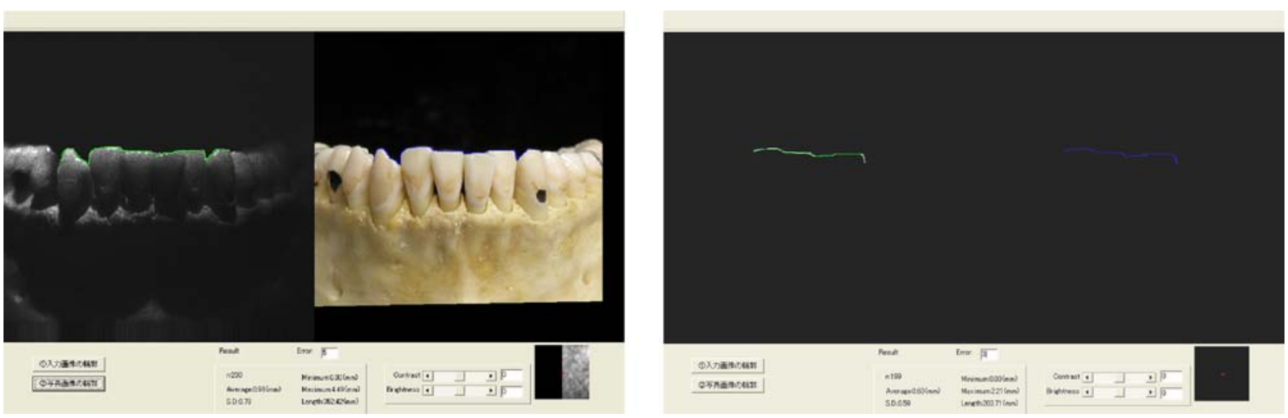

FIG. 10—*Measurement of the distance between the outlines of the different dentition images. The outlines of the two-dentition images were rendered by the basic spline function (left). The average value of the normal distances between the two outlines are indicated at the bottom (right).*

TABLE 5—*The distance between the outlines of six teeth superimposed by the 2D–3D and the video superimposition.*

		Right			Left		
	Dent	Canine	Lateral Incisor	Central Incisor	Canine	Lateral Incisor	Central Incisor
2D–3D	Average	0.29	0.31	0.11	0.12	0.29	0.3
	Min	0	0.14	0	0	0.14	0
	Max	0.71	0.59	0.33	0.3	0.49	0.64
Video Superimposition	Average	0.09	0.09	0.12	0.12	0.11	0.09
	Min	0	0	0.02	0	0	0.04
	Max	0.25	0.25	0.29	0.3	0.3	0.24

Units: mm.

substitute for the original object in forensic identification. Apart from the study by Evett (17), reports on forensic investigations using holography have been limited, presumably because of the complicated optical system used in recording large objects and the difficulty in utilizing the 3-D image itself. However, a holographic camera device is now available (7). Once the recording conditions are established, the recording can be performed without difficulty. Double-beam holography has the advantages of short exposure time and bright reconstructed image. Because the skull was too big for employing parallel lighting in our experiment, the real image could not be obtained; however, the virtual image of the skull could be seen in wide angle (Table 2). By contrast, the mandibula and the 6 study models could be recorded with a commercial concave mirror for parallel lighting, resulting in the successful reconstruction of the real images.

The virtual holographic image appears beyond the recording film and has transparency. In the present study, two methods using digital techniques were examined in order to evaluate the potential use of holographic images in superimposition, namely, the 2D–3D and video superimposition systems. In 2D–3D system, the raw 3-dimensional virtual holographic image was directly superimposed onto the photograph on the LCD monitor. Digital scaling of the photographic image was effective in achieving the superimposition. In the video system, the virtual holographic image was converted to a 2-dimensional image, which was then superimposed on the digitized photographic image. In this system, the conventional functions of fade out/in, etc., coming with the Rugle software, facilitated the matching. In dental superimposition, which has been reported useful for positive human identification (22)–(24), quantitative analysis using image processing software could bring higher reliability. Moreover, video superimposition is superior to the 2D–3D system because of the lower discrepancy between the images (Table 5). However, in actual cases, unlike this study, the data pertaining to the shooting conditions of the original photograph, namely, type of camera and lens, the distance from the subject, and so forth, would be hard to obtain. Thus, some discrepancies could remain in actual superimposition. In this study, the real holographic image was not utilized for superimposition; however, it should be suitable for quantitative inspection, such as the measurement of the distances between anatomical points, because cross-sections of the object can be observed on the screen in the reconstruction of the real image. On the other hand, the virtual holographic image can be intuitively and instantaneously judged as to whether it resembles the original object.

The performance of holography is comparable to that of the computer graphic system, which consists of an image scanner, software, and a display unit, and can even be superior to the computer technique in respect to the 3-dimensional reconstruction of images. Although the virtual image in the computer system can be easily manipulated 3-dimensionally, the observed images on the display are still 2-dimensional. Moreover, a fusion with the digital technique would potentially expand the utility of holography in superimposition.

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