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3D monochromatic image synthesized with vertical area-partitioned recording of master hologram in multiple-exposure holography

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Abstract

We report for the first time theoretical analysis and experimental results of a vertical-area partition method for recording master holograms in multiple-exposure rainbow holography to synthesize monochromatic 3D image from a series of medical tomograms. In this novel method, the master hologram is area partitioned into elementary master holograms, which are recorded in a periodic arrangement along the vertical direction. Under the white-light reconstruction, a 3D monochromatic image composed of a series of medical tomograms can be synthesized with wide viewing angle, high resolution, and low color blur. © 2001 Published by Elsevier Science B.V.

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1. Introduction

Two-step multiple-exposure rainbow holography can be employed to synthesize a 3D image from a series of 2D tomograms, where horizontal-area partition (HAP) method is used to record the master hologram with the multiple-exposure rainbow holography. That is, the master hologram is horizontally area-partitioned into a series of slitted elementary master holograms oriented in the ver-

tical direction. On each of which, a tomogram placed at the relative position correspondent to that in the original object is recorded. During the final white-light reconstruction, a 3D image can be seen through the simultaneous read-out of the multiple holograms [1–4]. Due to the dispersion, however, the reconstructed images from the different elementary holograms will appear in different colors and in different positional recovery, if no special treatment is accompanied. This kind of image distortion can easily result in false gray level and perspective judgments to human vision [5]. Some efforts have been made on to partially alleviate these disadvantages [6–8]. A method of inclining the master hologram [4,9] at the recording

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was proposed to eliminate this effect, and a dispersion compensation grating [10,11] has been employed to obtain achromatic reconstruction. All these methods need either complicated calculations or critical experimental conditions.

In this paper we report for the first time theoretical and experimental results of synthesizing monochromatic 3D images from a series of medical tomograms with vertical-area partition (VAP) method for recording the master hologram in the two-step multiple-exposure rainbow holography. By employing this VAP method, a 3D image, which consists of a series of monochromatic images of 2D tomograms, can be read-out simultaneously during the final white-light reconstruction. The monochromatic 3D image has the characteristics of wide viewing angles, high resolution, and little color blur.

In Section 2, a comparison between the constructions of HAP and VAP method for recording the master hologram will be presented, which is followed by the analysis of the difference of the viewing effect in Section 3. In Section 4, further analysis from the viewpoint of the dispersion windows of the both methods is introduced. Section 4 discusses about the resolution limit and the color blur of the VAP method. Experimental results of the 3D synthesis are given in Section 5. Finally, conclusions are made in Section 6.

2. HAP and VAP

We first briefly review the conventional HAP method and our VAP method in the first step for recording master hologram in a two-step multiple-exposure rainbow holography to synthesize 3D images.

In the HAP method, the master hologram is area-partitioned into a series of vertical slitted elementary holograms sitting side by side horizontally R_1 (along Y -direction, see Fig. 1(a)), with each slit recording a different tomogram, and the neighboring slitted elementary master hologram recording the successive frame of the 2D tomogram. Fig. 1(a) shows the optical layout of the HAP [3,12]. The master hologram H_1 is located in the XY -plane. A narrow vertical slit R_2 (it has its

length in X -direction) can be shifted in the Y -direction, which sets the region of the recording for each elementary master hologram.

In our VAP method, instead, the master hologram is area-partitioned into a series of horizontal slitted elementary master holograms along the vertical direction, by using a horizontal slit to set the recording regions of the elementary master holograms. The slit has its length along the Y -direction, and can be shifted in the X -direction during the successive recording of the elementary tomograms. The schematic diagram for the VAP method of recording the master hologram is shown in Fig. 1(b).

The rest of the procedures in both of these two methods are exactly the same. During the second recording step, (see Fig. 2), R_1^* , a conjugated reference beam to R_1 , is used to reconstruct the images of the tomograms recorded on H_1 . H_2 is placed at the central position of the reconstructed real images of the tomograms and illuminated by a recording reference beam R_2 . Therefore, the slits on H_1 and the reconstructed real images of the tomograms from H_1 will be recorded on H_2 . By the final white-light reconstruction, H_2 is illuminated by a collimated white-light beam on a conjugate direction and all the reconstructed tomograms can be viewed simultaneously through the respective real images of the slits. A 3D image composed of a series of tomograms is thus synthesized. R_3 : Besides, each of the reconstructed real images of the slits during the white-light reconstruction also sets a limit to the viewing field for observing the respective reconstructed image recorded on each elementary hologram.

3. Different viewing results

The optical setup systems recording the master holograms, R_4 : both in the case of HAP and VAP, are with the identical instrumental arrangement. The distance between the input objects (i.e., the 2D tomograms) and each of the elementary master holograms is much larger than the dimensions of each slit. Hence, the wave vector \vec{k} of the object wave can be considered approximately to be mainly along the Z -direction. The plane wave

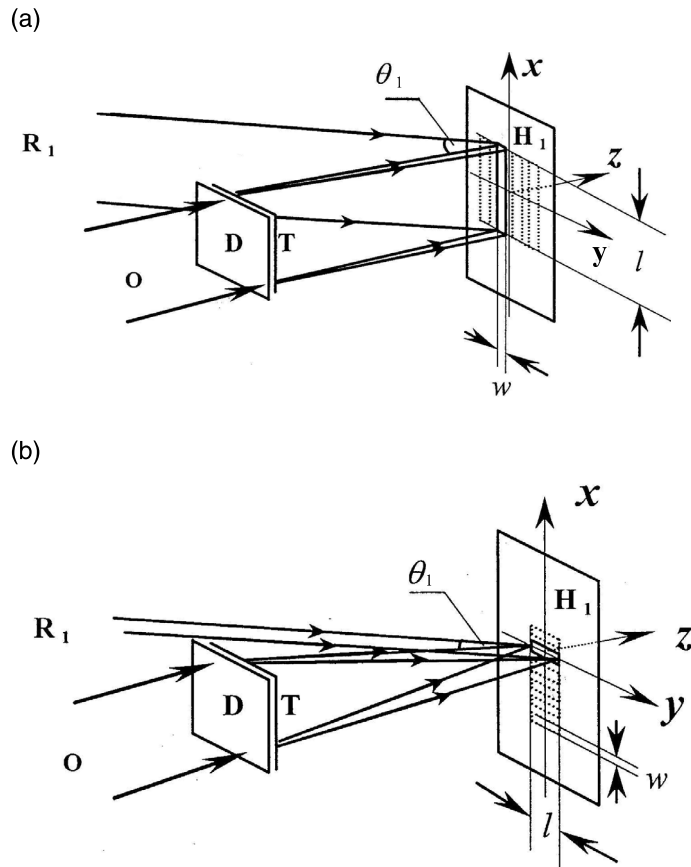


Fig. 1. Recording of slitted elementary master holograms: (a) HAP, (b) VAP (H_1 : master hologram, S: slits, R_1 : collimated recording reference beam, θ_1 : angle between reference and object beam, D: diffuser, O: object beam, T: tomogram).

reference beam, R_1 , for recording all the tomograms is perpendicular to the X -axis (see Fig. 1(a) and (b)). Consequently, the orientation of the interference fringes on the master hologram H_1 is mainly along the X -direction. The spacing of the interference fringes on the H_1 will, therefore, only depend on the angle between the normal of the reference wave vector and the Z -axis. Since the conditions of the optical waves for recording hologram H_2 is similar to that for recording the master hologram H_1 , the fringe orientation on the second hologram H_2 are similar to that of H_1 . Therefore, the dispersion of the reconstructed images during the final white-light reconstruction, R_5 : either in the case of HAP or VAP, will spread mainly along the Y -direction.

It is well known that the read-out of rainbow holography is based on the dispersion effect during the white-light reconstruction. By multiple-exposure rainbow hologram, the construction of the multiple slits on the H_1 should also be taken into consideration, for the orientation of the slits will also affect the viewing effect, and thus affect the final simultaneous read-out of the different 2D tomograms.

During the final white-light reconstruction step of the multiple-exposure rainbow hologram, R_6 : for both HAP and VAP all the real images of the slits on H_1 are reconstructed simultaneously in a form of observation window. Due to the dispersion effect, the observation window will disperse into a series of observation windows with different

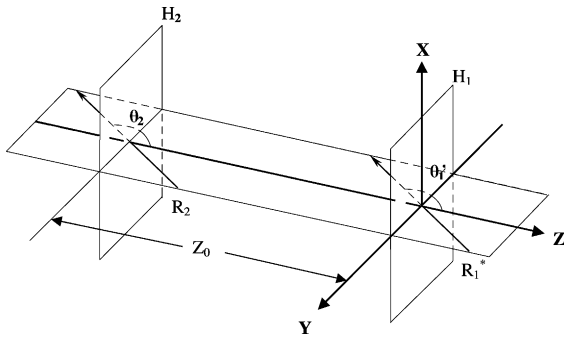


Fig. 2. Recording of H_2 . When master hologram H_1 is illuminated by a reconstructing reference beam R_1^* , real image of the tomograms can be reconstructed from H_1 . These images and the slits on H_1 will be recorded on H_2 (H_1 : master hologram, H_2 : hologram for second recording, R_1^* : reconstructing reference beam of H_1 conjugate to R_1 , R_2 : recording reference beam of H_2 , R8: θ_1' : angle between R_1^* and Z-axis, $\theta_1' = \pi - \theta_1$, θ_1 is the same angle as in Fig. 1, θ_2 : angle between R_2 and Z-axis, Z_0 : distance between H_1 and H_2).

colors. Depending on the orientation of the area-partition in recording the elementary master holograms, by HAP or VAP, however, the synthesized tomograms will have different viewing effects.

This can be analyzed quantitatively by using the Champagne's imaging equations [13], which hereon express the relation between the coordinates of a point real image reconstructed from H_1 or that of the central point of the related elementary master hologram on H_1 in the second recording, (x_0, y_0, z_0) , and that of the corresponding image reconstructed from H_2 (x_i, y_i, z_i) during the final white-light reconstruction:

$$x_i = x_0 \quad (1)$$

$$y_i = y_0 - z_0 \sin \theta_2' [(\lambda_0/\lambda_i) - 1] \quad (2)$$

$$z_i = (\lambda_0/\lambda_i)z_0 \quad (3)$$

R7: where θ_2' is the angle to Z-axis of the final reconstructing beam complementary to that of the final recording, θ_2 , λ_0 is the optical wavelength used for the recordings and λ_i represents the wavelength included in the white-light reconstruction. It can be seen from Eqs. (1)–(3) that, both in the case of HAP and VAP, with different

optical reconstruction wavelengths, the center position of a reconstructed slit or the tomogram recorded within it will shift along the Y and the Z-directions, but remain the same in the X-direction. This effect is demonstrated in Figs. 3 and 4, respectively, where each observation window is composed of the reconstructed slits with the same value of λ_i (same x_0 and different y_0 in Fig. 3 for HAP, or same y_0 and different x_0 in Fig. 4 for VAP). It is noticed that different windows in different wavelengths shift along the directions of Y and Z, according to Eqs. (2) and (3). The locus of the centers of the observation windows in different wavelengths traces a straight line at an angle α to Z-axis. By substituting Eq. (3) in Eq. (2), the α can be calculated:

$$\tan \alpha = \sin \theta_2' \quad (4)$$

This expression is similar to that of the achromatic angle in achromatic holographic stereogram reported by Benton [9].

Thus, by the HAP approach, the whole series of the reconstructed images of the tomograms have to be viewed simultaneously through the respective real images of the slits in different viewing windows, along, or with a angle much less than α , to Z-axis (see Fig. 3). As a result, the rainbow effect and false positional recovery will be seen among the depth of the synthesized 3D image. This may easily result in a false judgement of gray level and perspective recovery to human eyes, due to the human photopic eye response [5].

By the VAP approach, the dispersion effect of the reconstructed images will also remain along the Y-direction and Z-direction. However, the direction of the dispersion is vertical to that of the area-partition, the X-direction. Therefore, each of the dispersed windows can be viewed at different viewing angles within the image field of the reconstructed tomograms, other than α , to Z-axis without overlapping, and all the reconstructed 2D tomograms can be viewed simultaneously with one wavelength through a single viewing window (see Fig. 4). Consequently, the rainbow effect as well as the false positional recovery will not appear among the different depths of the synthesized 3D images.

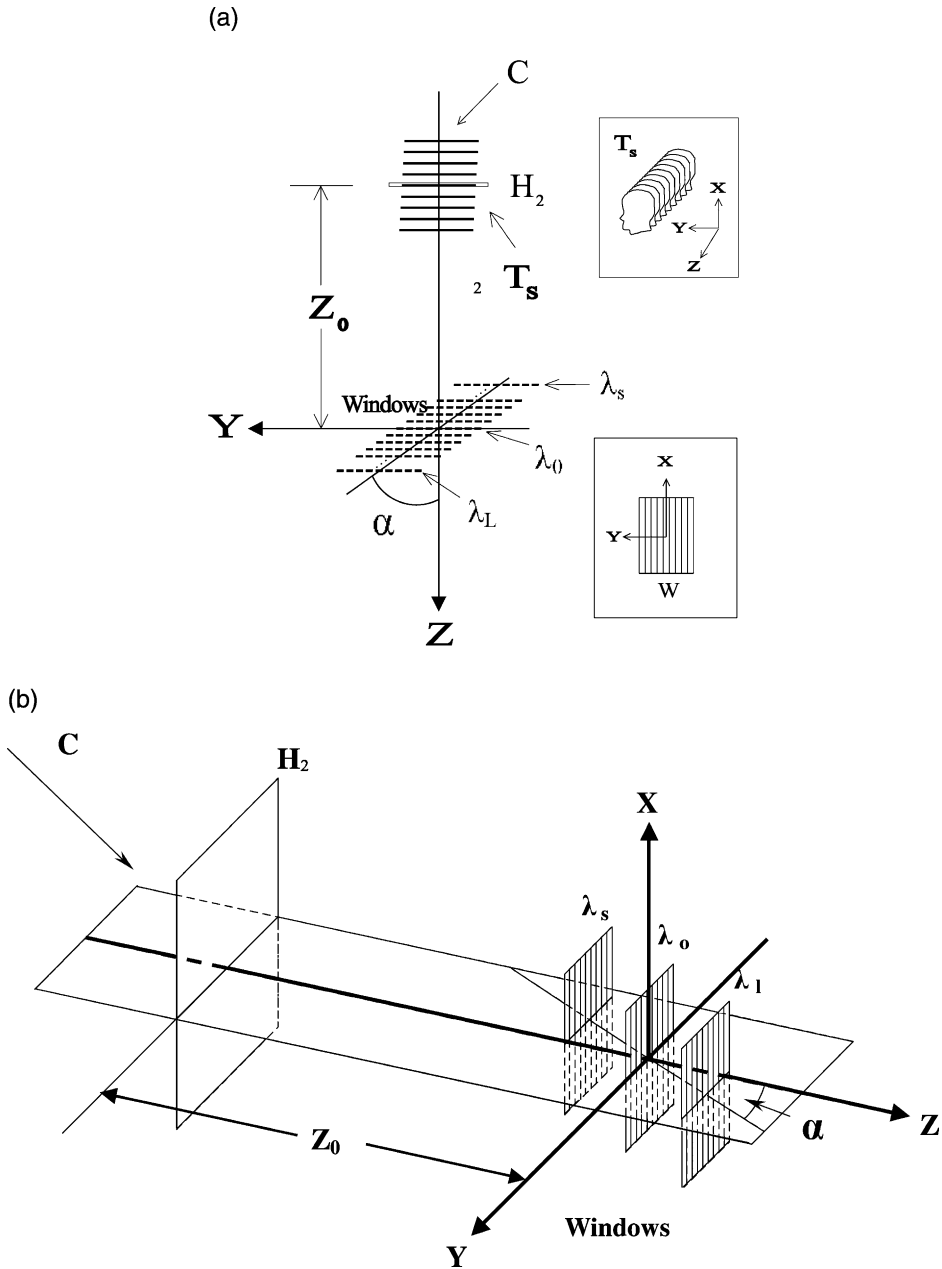


Fig. 3. Observation windows in white-light reconstruction and viewing effect of HAP: (a) top view, (b) perspective view. By the white-light reconstruction of H_2 , all the real images of the slits on the master hologram H_1 will be simultaneously reconstructed in the form of observation window, which will be dispersed into a series of windows with different wavelengths along a straight line at an angle α to Z -axis. A series of corresponding reconstructed images of the tomograms can be only viewed through different observation windows with different wavelengths, resulting in a rainbow distribution among the depth of the synthesized 3D image. Besides, false recovery of position will appear generally, due to the relative distribution of the dispersed windows shown in the illustration, as an example (H_2 : holograms for reconstruction, α : dispersion angle, C: white-light for reconstruction, W: construction of the observation window, Ts: reconstructed images, R9: viewed along $-Z$ direction, Z_0 : distance between H_2 and the observation window of λ_0 , λ_0 : wavelength same as in the recordings, λ_1 : longer wavelength than in the recordings, λ_s : shorter wavelength than in the recordings).

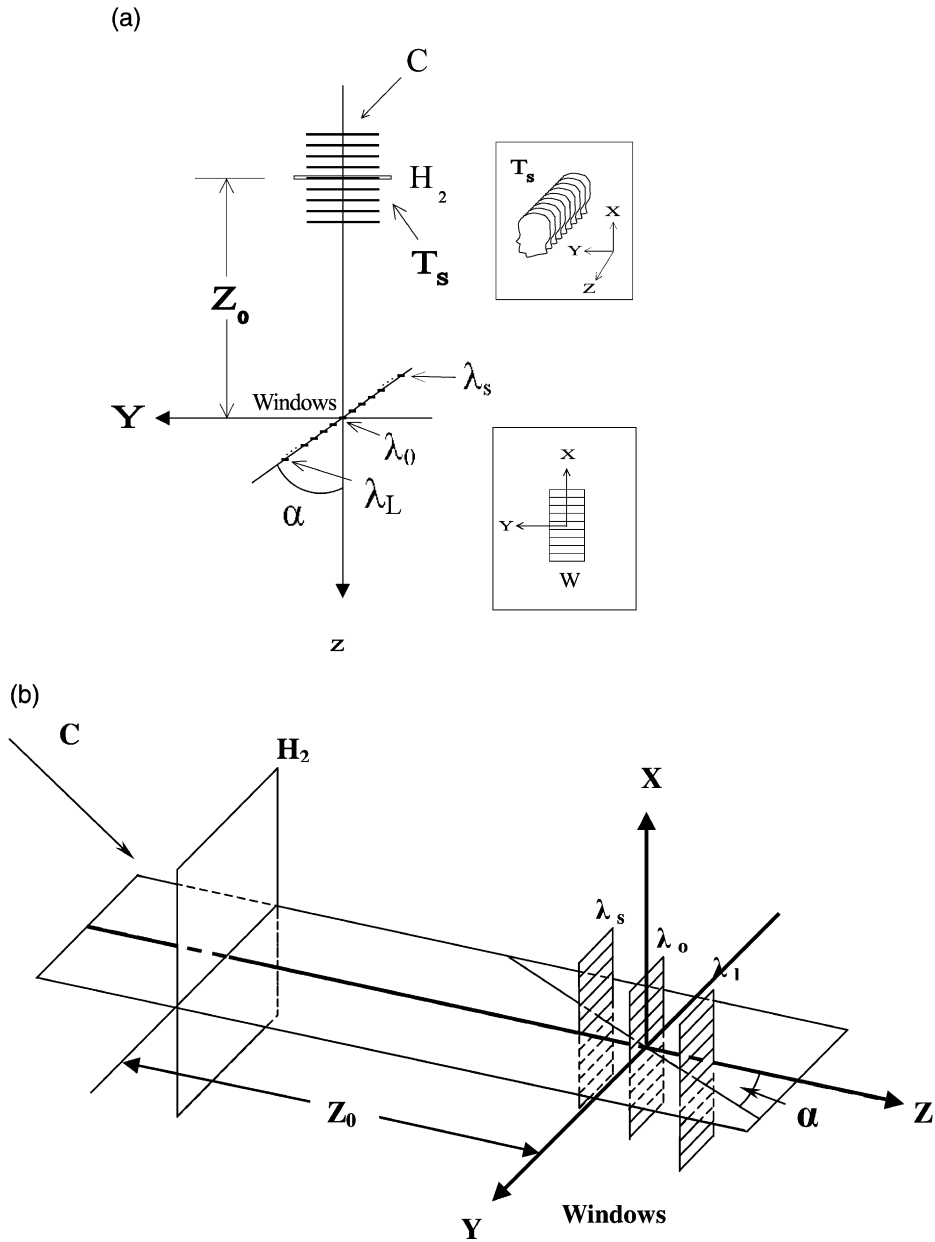


Fig. 4. Observation windows in white-light reconstruction and viewing effect of VAP: (a) top view, (b) perspective view. By the white-light reconstruction of H_2 , all the real images of the slits on the master hologram H_1 will be simultaneously reconstructed in the form of observation window, which will be dispersed into a series of windows with different wavelengths along a straight line at an angle α to Z -axis. All the reconstructed images of the tomograms can be viewed through only a single window with the identical wavelength. No rainbow effect or false positional recovery will be observed at any possible viewing angle, other than α , R10: which ensures a monochromatic synthesis of the 3D image with better resolution. A series of reconstructed images, T_s , is shown in the top of the figure observed along the $-Z$ direction, as an example (H_2 : holograms for reconstruction, α : dispersion angle, C : white-light for reconstruction, W : construction of the observation window, T_s : reconstructed images viewed along $-Z$ direction, Z_0 : distance between H_2 and the observation window of λ_0 , λ_0 : wavelength same as in the recordings, λ_1 : longer wavelength than in the recordings, λ_s : shorter wavelength than in the recordings).

4. Resolution of the reconstructed images by VAP

It is known that the resolution and the color blur of a rainbow hologram are generally related to the slit diffraction [14]. For the VAP approach, the vertical diffraction is limited by w , the width of the slits on H_1 . The resolution limit of the reconstructed image can be approximately expressed by [15]

$$E_i = \lambda_i(Z_0 - Z_{0i})/w \quad (5)$$

where Z_0 is the distance between H_2 and H_1 , Z_{0i} is the distance between H_2 and the real image of the i th tomogram reconstructed from H_1 , at the second recording, and λ_i is one of the wavelength components included in the white light for reconstruction. By substituting the experimental conditions of VAP, $\lambda_i = 550$ nm, $Z_0 = 500$ mm, $|Z_{0i}| \leq 30$ mm, and $w = 3$ mm, into Eq. (5), the minimal resolvable spacing is calculated as $E_i \leq 0.1$ mm. Since the physical limitation of human vision is not as good as 0.1 mm, hence the diffraction effect caused by the slitted elementary holograms can be neglected, as long as the width of the slit w is at least 3 mm.

The color blur due to the horizontal dispersion is affected by l , the length of the slit. Assuming that the eye is located at the real image of the slit and that the eye pupil is much smaller than l , Yu [15] has shown that the length of the spectrally dispersed image in Y -direction of one object point can be given by:

$$\Delta y \approx Z_{0i}l/Z_0 \quad (6)$$

which can be considered as the resolution limit of the image. Eq. (6) implies that a higher resolution along the horizontal direction can be obtained by reducing the slit length l , at the cost of losing brightness of the reconstructed images.

A balance between the resolution and the brightness of the reconstructed images can be achieved by optimizing the width and the length of the slitted elementary master holograms. Besides, periodic groups of slitted elementary holograms can be recorded repeatedly in a cycle structure, so that the effective total recording area and, conse-

quently, the brightness of the reconstructed images is enlarged.

5. Experimental results

In the first step of the experiment, the VAP approach is employed to record the slitted elementary master holograms on H_1 . To record H_2 in the second step, H_1 is illuminated by a reference beam conjugate to that used for recording H_1 . Thus, a series of real images of the 2D tomograms were obtained. The holographic plate for recording H_2 is positioned at Z_0 , the center of these real images, so that quasi-image holograms and an image-hologram at the position of the plate, of the real images, as well as the slits on H_1 as objects, are recorded on H_2 .

Coherent light of the wavelength 532 nm from a Verdi laser was used for all the holographic recordings. All the holograms were recorded with silver-halide emulsion plates of type TJ-III made in Tianjin, China. In the recordings, the hologram plates were placed on the X - Y plane and the reference beam will be kept at an angle of $\theta_2 = 28^\circ$ to Z -axis or complementary to that. At the second recording, H_2 was recorded at a distance of $Z_0 = 500$ mm away from the master hologram H_1 , which was at the same value of the distance between H_1 and the center of the tomograms series in the first recording. In this way, different series of medical tomograms are used to synthesize 3D monochromatic images by VAP approach. A circulation technique is employed to periodically record the slitted elementary master hologram. That is, to synthesize a series of 20 pieces of human knee-joint tomograms with this technique, the recording area of the master holographic plate of 240×30 mm² is area-partitioned into 80 slitted elementary holograms, which are divided into four periodic groups along the vertical direction with 20 slits in each period. In this way, each tomogram will be repeatedly recorded in four respective elementary master holograms, which offers a larger effective recording area, so that higher brightness of the reconstructed images and wider viewing angles of the final read-out in the white-light



Fig. 5. Monochromatic 3D image synthesized from 15 pieces of human brain tomograms by VAP approach.



Fig. 6. Monochromatic 3D image synthesized from 20 pieces of human knee-joint tomograms by VAP approach.

reconstruction can be achieved. For the series of 15 pieces of human brain tomograms, a master holographic plate of $180 \times 30 \text{ mm}^2$ is area-partitioned in the same way.

Figs. 5 and 6 show, respectively, the monochromatic 3D images synthesized from 15 pieces of human brain tomograms and 20 pieces of human knee-joint tomograms. As can be seen from the figures, there is no distortion in gray levels and in position recovery. Also the brightness and resolution appear to be satisfactory for the medical inspection.

6. Discussions and conclusions

We have reported and demonstrated a VAP method for recording master holograms in the multiple-exposure rainbow holography. This technique has been successfully used to synthesize monochromatic 3D images from a series of medical 2D tomograms by a white-light reconstruction. Our theoretical and experimental results show an advantage of the VAP method over the conventional HAP method that any false recovery in gray levels or position will not be induced within the viewing field of the synthesized mono-chromatic 3D image, without carrying out any extra experimental arrangement or complicated theoretical calculations.

In order to alleviate the horizontal color blur during the white-light reconstruction for higher resolution, the slit for recording the master hologram should be maintained within a certain length. The reduction in the brightness can be compensated for by a circulation technique of periodic recording. This technique can further provide a wider viewing angle in the vertical direction.

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