Three-Dimensional Image Display Without Special Eyeglasses: Observation of Magnetic Resonance Angiography Using the Stereoscopic Liquid Crystal Display

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The authors have developed a new stereoscopic liquid crystal display that provides real-time 3-dimensional image viewing without special eyeglasses. The device consists of 3 major parts: (1) an image display composed of a 10.4-inch color liquid crystal plate with a resolution of 640×480 , (2) an automatic head tracking system, and (3) a special backlight unit for the right and left eyes. Eight radiologists interpreted 60 cases of magnetic resonance angiography (29 cases of cerebrovascular disease and 31 normal cases) to compare film display and the liquid crystal display (ie, pseudo 3-dimensional display and true 3-dimensional display). Using a continuously distributed scale ranging from 0% to 100%, the observers ranked their confidence levels in determining the presence or absence of steno-occlusive disease, aneurysm, and arteriovenous malformation (AVM) and their locations. For statistical evaluation, receiver operating characteristic (ROC) analysis and Brier score were used. For detecting AVM, film reading showed a significantly higher value in the area under the binormal ROC curve (Az) than did pseudo-3-dimensional display ($P < .05$). Excluding this, however, no significant difference existed in Az values among the 3 viewing methods. Also, there was no significant difference in Brier score between not only the stereoscopic view and nonstereoscopic view groups, but also the senior and junior groups. Subjective estimation of true 3-dimensional display showed that vessels were more distinguishable with less eye fatigue compared with stereoscopic film reading. The stereoscopic liquid crystal display provided almost equal efficacy to film reading; however, the short optimum distance for observation and the low resolution should be improved.

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THERE ARE a lot of approaches to visualize 3-dimensional (3D) images. They are divided into 2 methods: true 3D display and pseudo-3D display. The shading or perspective technique that simulates spatial position by computer

graphics is pseudo-3D display. In contrast, stereoscopic technique provides true 3D display applied with binocular disparity or optical technique.¹⁻³ Stereoscopic display is more realistic and superior to pseudo-3D display in recognizing spatial position.⁴⁻⁶ As for medical applications, it is applied to diagnostic images such as stereoscopic angiography,⁷⁻¹¹ magnetic resonance imaging (MRI), computed tomography (CT),¹²⁻¹⁴ and 3D video endoscopic systems, and is used for not only diagnosis but also minimally invasive surgery.^{15,16} Currently, stereoscopes with special eyeglasses are used widely to view a 3D image. However, wearing special eyeglasses is very inconvenient, especially for the usual eyeglasses user. We have developed an advanced stereoscopic liquid crystal display (Sea Phone 3D display, Sea Phone, Gifu, Japan) that permits observation of stereoscopic images by several persons simultaneously without special eyeglasses and any kind of head tracking devices for viewers.

We already have reported about the principle of the device, basic performance, and optimization of monitor size.¹⁷⁻²³ It has been applied to a stereoscopic television conference between Duke University Medical Center (United States) and the Department of Radiology, Nagoya University

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Fig 1. Diagram of a stereoscopic liquid crystal display. This display permits observation of stereoscopic images by several persons simultaneously without special eyeglasses.

School of Medicine (Japan) using a high-speed digital line of Global International Broadband Network (GIBN).²⁴ In this report, we evaluated the clinical usefulness of 3D-displayed images using this device.

MATERIALS AND METHODS

Sixty patients who underwent magnetic resonance angiography (MRA) from April 1995 to October 1996 were selected for the study (29 cases of cerebrovascular diseases and 31 normal cases). Cerebrovascular diseases included 10 cases of stenocclusive disease with a single lesion in each case, 10 cases of aneurysm with 11 lesions (one case was both stenocclusive lesion and aneurysm), and 10 cases of arteriovenous malformation (AVM) with single or multiple lesions. All these lesions were confirmed by cerebral angiography. In 31 normal cases, MRA and routine MRI results were interpreted as "normal" by 2 board-certified radiologists.

All examinations were performed using a 1.5-T MRI system (Visert, Toshiba, Co, Tokyo, Japan). Data acquisition for the head MRA was done using 3D time-of-flight technique with a head coil, and angiographic images were reconstructed by maximum intensity projection (MIP) algorithm. For each case, 7 projection images were reconstructed at each 6° with a total angle of 42°. Collapse images were not used. The disparity of the device was adjusted to 6° because the optimum disparity is 6° for stereoscopic viewing.²⁵ Because the purpose of this study was to compare the performance of 3D image display, only MIP images were interpreted.

The stereoscopic liquid crystal display consisted of 3 major parts: (1) A 10.4-inch color liquid crystal plate of transparent type with a resolution of 640 × 480; (2) an automatic head tracking system composed of an infrared illuminator, a camera, and an image circuit; and (3) a special back light unit composed of a monochrome liquid crystal plate and a large format convex lens for each eye (Fig 1). An infrared illuminator (830 to 870 nm) projected the observer. The infrared image was focused on the diffuser by a Fresnel convex lens and was captured by an

infrared camera. The image circuit modulated it and produced binary half right and left face images. Each image was distributed to the monochrome liquid crystal plate of the back light unit, and lighted to each of the observer's eyes. A half mirror combined the stereo-pair images. Therefore, the device had an automatic head tracking system and permitted observation of stereoscopic images by several persons simultaneously without special eyeglasses. The viewing angles of this device were 37.2 degrees in the horizontal direction and 28.3 degrees in the vertical direction. The viewing area was 20 to 100 cm (the optimum distance was 50 cm). The frame rate was 30 frames per second for the right image and the same for the left image.

The MIP images were put but in National Television Standards Committee (NTSC) signals from the MRI scanner and stored on magnetic optical disks. Two disks in which the same images were stored were prepared for the device. One was for the right eye and the other was for the left eye as stereo-pair images. True 3D images as stereo-pair images were displayed by inputting 2 images with a disparity of 6°, whereas pseudo-3D images could be displayed by inputting the same images for each eye. It took 0.8 seconds to display both true 3D images and pseudo-3D images.

Eight radiologists interpreted these images independently without any knowledge of their diagnoses. Four of the observers were board-certified radiologists (senior group). The others had less than 2 years' experience (junior group). Seven MIP images (6 stereo pairs) per case were interpreted by 3 viewing methods: (1) film reading (4 radiologists interpreted with the stereo-view method and the other 4 without the stereo-view method), (2) pseudo-3D display reading (nonstereo-view by the device), and (3) true 3D display reading (stereo-view by the device). They were evaluated in variable turn at 1-month intervals. No time limit was imposed on the interpretation. One image was displayed at a time, and turning of images was permitted.

The observers described their confidence level as to the presence or absence of stenocclusive disease, aneurysm, and AVM using a continuously distributed scale that ranged from 0% to 100%. The reading time was measured. For stenocclusive lesion and aneurysm, 9 arteries evaluated included

bilateral internal carotid arteries, anterior cerebral arteries, middle cerebral arteries, posterior cerebral arteries, and the basilar artery. The location of the nidus of AVM was described as one of the following 8 parts: bilateral anterior lobe, temporal lobe, posterior lobe, and parietal lobe.

To evaluate the diagnostic performance of the 3 viewing methods, the receiver operating characteristic (ROC) analysis²⁶⁻³⁰ and the Brier score³¹⁻³⁴ were used. For statistical analysis, the area under the binormal ROC curve (A_z), calculated by maximum likelihood estimation,²⁶ was used as an index of performance. Average ROC curves were obtained by averaging the binormal slopes and the intercept parameters of the individual observer's ROC curve. Statistical evaluation was performed with the method described by Hanley and McNeil.²⁸ The statistical significance was judged at P less than .05. The Brier score provides a score that quantifies the accuracy of a set of judgments, by comparing the expressed probabilities with the actual outcomes. The smaller the Brier score, the better the performance. For statistical analysis, 2-way analysis of variance with no repeated measures was used.

RESULTS

Reading time for each observer varied from 45 to 100 minutes (average, 68 minutes) at film display, 60 to 87 minutes (average, 69 minutes) at true 3D display, and 36 to 160 minutes (average, 76 minutes) at pseudo-3D display. The reading times of film interpretation and of true 3D display were almost equal. The average reading time of pseudo-3D display was the longest; however, inter-observer variance in reading time was large. There were no statistically significant differences in reading time among the 3 viewing methods.

Fig 2. ROC curves: steno-occlusive lesion. Note: There was no significant difference among A_z s.

Fig 3. ROC curves: aneurysm. Note: There was no significant difference among A_z s.

ROC analysis showed that the diagnostic performance of pseudo-3D display was the highest in detecting steno-occlusive lesions among the 3 viewing methods, and that the diagnostic performance of film was the highest in detecting aneurysm and nidus of AVM (Figs 2, 3, and 4). There was a significant difference in A_z values between film and pseudo-3D display in detecting nidus of

Fig 4. ROC curves: nidus of arteriovenous malformation. Note: There was a significant difference in A_z s between film reading and pseudo-3D display ($P < .05$).

Table 1. Total Brier Score

Display Type	Steno-Occlusive Lesion	Aneurysm	Nidus
Film	0.0195 $\pm$ 0.0039	0.0104 $\pm$ 0.0018	0.0249 $\pm$ 0.0041
Pseudo-3D display	0.0219 $\pm$ 0.0039	0.0130 $\pm$ 0.0018	0.0248 $\pm$ 0.0041
True 3D display	0.0234 $\pm$ 0.0039	0.0121 $\pm$ 0.0018	0.0250 $\pm$ 0.0041

Note. Mean $\pm$ 95% confidence interval.

AVM; however, there was no significant difference between pseudo-3D display and true 3D display for any lesion.

As for Brier score, the performance of film reading was somewhat better than pseudo-3D display and true 3D display in the detection of steno-occlusive lesion and aneurysm, without significant differences (Table 1). The Brier scores were almost equal among the 3 viewing methods in the detection of nidus of AVM. No significant differences were found between the stereo-view and nonstereo-view film reading groups (Table 2), and between the senior and junior groups (Table 3).

As for subjective estimation of true 3D display using the device, images could be seen more realistically, and vessels were more detectable. Observers described some advantages: (1) it was easy to differentiate aneurysms from curving vessels and stenosis from the decreased signal intensity by artifacts at curved points, (2) displacement of vessels and feeding arteries of AVM were observed easily, (3) eye fatigue with the stereo-view method was less than with film reading. However, some defects were pointed out: (1) it took several seconds to adjust the observer's eye position to get the optimal distance between observer and monitor for viewing 3D images, because the range of optimum viewing distance is narrow; (2) the resolution of the display was not very high; (3) there was a little "cross talk," in which images were distributed not to only one eye but

to both. Similarly, pseudo-3D display had the same defects as true 3D display, although the spatial positions of vessels were understandable by turning images with the pseudo-3D display.

DISCUSSION

Generally, true 3D images have the advantage that spatial positions of vessels are more understandably displayed compared with pseudo-3D images. Although the observers' performance of film reading tended to be somewhat better than that of true or pseudo-3D display, a significant difference in Az values existed only between film and pseudo-3D display in detecting nidus of AVM. The reasons for this were considered: detection of steno-occlusive lesion or aneurysm was not difficult given knowledge of anatomic structure, whether the display method was true 3D display or pseudo-3D. As for the interpretation of AVM, feeding arteries were abnormal, tortuous vessels; therefore, true 3D display was more informative about the 3D positional relationships of complicated vascular structures compared with pseudo-3D display.

However, the learning effect in 3D image interpretation has been discussed.^{35,36} There were no significant differences in Brier scores among the 3 viewing methods, not only with or without stereo-view in film reading but also between the senior and junior groups. This indicates that the learning effect was minimal for using the device, and that the device provided almost equal efficacy to film reading.

Table 2. Brier Score Comparisons: Film Reading With or Without Stereoscopic Viewing Groups

Display Type	Steno-Occlusive Lesion	Aneurysm	Nidus
Stereoscopic-view group			
Film	0.0188 $\pm$ 0.0054	0.0111 $\pm$ 0.0031	0.0247 $\pm$ 0.0076
Pseudo-3D display	0.0205 $\pm$ 0.0054	0.0141 $\pm$ 0.0031	0.0235 $\pm$ 0.0076
True 3D display	0.0233 $\pm$ 0.0054	0.0117 $\pm$ 0.0031	0.0245 $\pm$ 0.0076
Nonstereoscopic-view group			
Film	0.0201 $\pm$ 0.0071	0.0097 $\pm$ 0.0025	0.0251 $\pm$ 0.0057
Pseudo-3D display	0.0234 $\pm$ 0.0071	0.0117 $\pm$ 0.0025	0.0261 $\pm$ 0.0057
True 3D display	0.0235 $\pm$ 0.0071	0.0126 $\pm$ 0.0025	0.0255 $\pm$ 0.0057

Note. Mean $\pm$ 95% confidence interval.

Table 3. Brier Score Comparisons: Senior Group Versus Junior Group

Display Type	Steno-Occlusive Lesion	Aneurysm	Nidus
Senior group			
Film	0.0181 $\pm$ 0.0073	0.0095 $\pm$ 0.0028	0.0218 $\pm$ 0.0049
Pseudo-3D display	0.0200 $\pm$ 0.0073	0.0120 $\pm$ 0.0028	0.0236 $\pm$ 0.0049
True 3D display	0.0200 $\pm$ 0.0073	0.0102 $\pm$ 0.0028	0.0213 $\pm$ 0.0049
Junior group			
Film	0.0208 $\pm$ 0.0031	0.0113 $\pm$ 0.0022	0.0280 $\pm$ 0.0064
Pseudo-3D display	0.0239 $\pm$ 0.0031	0.0139 $\pm$ 0.0022	0.0260 $\pm$ 0.0064
True 3D display	0.0268 $\pm$ 0.0031	0.0140 $\pm$ 0.0022	0.0286 $\pm$ 0.0064

Note. Mean $\pm$ 95% confidence interval.

As for subjective estimation of the device, true 3D display was excellent for displaying 3D images realistically. However, there were some problems to be improved, such as short optimum viewing distance, low resolution, and eye fatigue, with both true 3D and pseudo-3D display.

The optimum viewing distance was adjusted to about 50 cm from the display. If the observer gets too close to the display, 3D images get distorted and darken. In conventional film reading, observers sometimes approach films closely to interpret images precisely, but this style does not suit this device. A function to change magnification of images freely should be developed.

In image processing, 2 factors affect image quality: (1) the change of image data into NTSC signals, and (2) low resolution of the liquid crystal plate. The device needs image data sets of NTSC signals. Hence, a decrease in image quality in generating NTSC signals cannot be avoided. Also, the liquid crystal plate is of lower quality than film in both spatial resolution and contrast resolution. However, the technologic development in this field has been remarkable, and new liquid crystal plates with higher performance and quality are expected in the near future.

Incidentally, stereopsis itself can cause symptoms such as eye fatigue, headache, head heaviness, and dizziness with any device, because ste-

reopsis includes an inherent imbalance between convergence by the ocular muscles and accommodation by the lenses.³⁷⁻³⁹ The convergence point is on the reproduced stereoscopic image, whereas the accommodation point is on the surface of the display. Because the difference produces the stereoscopic 3D image, some fatigue is induced from the imbalance. Fatigue, however, can be reduced by improvements in image quality, display performance, and the situation of observation.³⁸ Subjective estimation showed that fatigue by the device was lower than that by film with the stereo-view method. Our 3D display device needs neither convergence nor special eyeglasses, resulting in the reduction of fatigue.

CONCLUSION

The usefulness of stereoscopic liquid crystal display was evaluated in the interpretation of 3D head MRA. Subjective estimation of true 3D display was good, because the 3D positional relationships of complicated vascular structures were more distinguishable with the reduction of eye fatigue compared with film reading. There was no significant difference in ROC analysis or in Brier scores between true 3D display and film reading. The short optimum distance for observation and low resolution of the liquid crystal plate should be improved for clinical use.

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