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Lenticular System: Full-Color, Limited-Angle, Autostereoscopic Alternative to Holography¹

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A sample lenticular image appears on page 400A.

The microlenticular system is a method of hard copy imaging that provides stereoscopic cues without the use of special glasses or viewing devices. Therefore, it is called an autostereoscopic technique. The microlenticular system consists of a layer of cylindric lenses combined with a photographic emulsion that carries three to seven different two-dimensional views of the same three-dimensional (3D) scene. Since each of the observer's eyes sees a different view, the resulting image is perceived as being 3D. The microlenticular system technique can be traced back to 1908 but was recently revived because of inventions that allow automatic photographic printing of this type of hard copy. The technique has been applied to visualization of medical 3D images obtained with the following modalities: computed tomography (CT), magnetic resonance imaging, single photon emission CT, ultrasound, scanning electron microscopy, laser scanning, and confocal laser microscopy. Use of this technique results in images suitable for planning complex surgery and for simplifying the communication of complex geometries in science and education.

■ INTRODUCTION

The first stereoscope was described by Sir Charles Wheatstone in a lecture to the Royal Society of London on June 21, 1838 (1). The concept was refined by Sir David Brewster, who presented the first stereoscope to make use of refraction (2) to the Scottish Royal Society on March 24, 1849. By 1860, his handheld version had evolved into the popular Holmes stereoscope. In March 1896—shortly after Röntgen's discovery of x rays in 1895—Elihu Thomson suggested that stereoscopy be applied to radiography (3). The Holmes stereoscope was later extensively used for viewing photographs of radiographs (4,5) (Fig 1).

An interesting aspect of early stereoscopic radiography is that it was used directly in patient treatment, namely, to precisely localize foreign bodies before removal (6). Later (1943–1970), stereoscopic radiographs were also used for diagnostic purposes, especially in cases of complex entities such as orbital fracture (7,8), by moving the x-ray

Abbreviations: 3D = three-dimensional, 2D = two-dimensional

Index terms: Images, display • Images, processing • Stereoscopic display

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Figure 1. Photograph shows a Holmes stereoscope with angiographic stereo images of cadaveric specimens that were injected with contrast medium (4).

tube about 6 cm between two exposures at a distance of about 75 cm from the patient (8). A criticism of stereographic radiography was that the transparency inherent in radiographs significantly reduced the stereoscopic effect from a visual perception point of view (9). The best results were obtained with highly contrasting structures such as the vessels in cerebral angiography (10). When tomographic imaging was perfected in the form of computed tomography (CT), stereoscopic radiography retreated into obscurity.

For reasons of clarity, we will refer to the two-dimensional (2D) views of a three-dimensional (3D) scene that constitute a stereogram and that are meant to be viewed by separate eyes as "2D aspects."

Although many different techniques have been developed for the generation of binocular stereoscopic hard copies (11), most parallel techniques use visual fusion of separate 2D aspects (the Brewster technique), except for the anaglyph or color-coding technique (red and green 2D aspects are superimposed and are observed by using glasses with a green and a red "lens") and the "Polaroid Vectograph" or polarization-encoding technique (in which special Polaroid glasses are used) (8). The sequential techniques in which mechanical or electronic

Figure 2. Diagram shows the basic shape of the lenticular system including a photographic emulsion.

shutters are used are obviously not suitable for hard copies. The need to use a viewing device, such as a stereoscope or a pair of special glasses, was also considered to be disadvantageous. Therefore, early in this century, autostereoscopic methods were explored to eliminate the need for these special devices.

The solution to the problem of autostereoscopic viewing was based on the fact that each eye has its own position (ie, the viewing direction is slightly different for each eye when one looks at the same point in a 3D scene). Thus, the problem was reduced to the question of whether it was possible to view different 2D aspects of a 3D scene when one looks from different directions. An affirmative answer was provided by making use of refraction in the form of a lenticular screen or lenticular system, which was patented by Walter Hess in 1912 (12). Different techniques such as "parallax stereography" and "parallax panoramagraphy" were developed by using other recording methods (13,14). These techniques were the forerunners of the lenticular system in its current form, which consists of a transparent sheet with narrow, vertical, cylindric lenses on one side (lenticular sheet) and a photographic emulsion on the other side (Figs 2-4). During the recording phase, the lenticules themselves are used to focus the light onto the emulsion.

The lenticular system is a derivative of "integral photography," which was invented by M. G. Lippmann in 1908 (15). Integral photography permits recording of the spatial informa-

Figure 3. Diagram shows a horizontal cross section through the eyes of an observer perpendicular to the lenticular screen. Superimposition of the imaged object (a patient's skull) shows how the correct illusion of depth is created as points in the foreground (*F*) and background (*B*) are projected onto different places on the lenticular screen depending on their position in space. *C* = center, *L* = left eye 2D aspect, *R* = right eye 2D aspect.

Figure 4. Diagram shows the optic geometry of a single lenticule. The three light beams, shown in three different colors, represent the light that is emitted from the same point on three different 2D images and in three different directions. This diagram demonstrates the principle of direction dependability of the visualization of a specific 2D view and also shows how multiple 2D views can be combined into a single image layer.

tion of a 3D scene on a flat photographic sheet in such a way that it can be viewed stereoscopically without use of special aids such as a stereoscope. This was basically a forgotten technique that, in its original form, reemerged in the 1960s. The principle involves a sheet with a large number of tiny, convex lenses (fly's-eye lens sheet) in the focal plane of which as many tiny pictures are recorded as there are lenses (eg, 20,000). After the film is developed and printed one-to-one in positive and placed again in the focal plane of the fly's-eye lens sheet, it can be viewed. Depending on the vantage point of the observer, a different corresponding 2D aspect is seen because each lens shows only one point of its tiny picture, the one that corresponds to the observer's position. After 1928, attempts were made to simplify the fly's-eye lens sheet by abandoning the parallax in the vertical direction to create a system that is much simpler to manufacture. The invention of the resulting lenticular screen cannot be accredited to a single inventor, but F. E. Ives and his son H. E. Ives were important contributors (16).

In the 1950s, early lenticular images became popular and were used in Hollywood for promotional purposes in the form of large, transparent autostereograms of movie stars (17). Even the moon was visualized with the lenticular system (18).

Originally, a multiple-camera setup recorded the 2D aspects of the 3D scene, but eventually a multilens camera was developed by Allen K. W. Lo (19,20). This type of photographic setup produces as many negatives as there are lenses, thus creating 2D aspects of the 3D scene at different viewing positions. Each of these negatives is subsequently used to project an image onto an unexposed lenticular system in a direction that corresponds to the direction in which that particular negative was created. This procedure is then repeated for the other negatives in their respective directions. Finally, the emulsion of the lenticular system is developed. In 1987, Lo discovered that the number of these lenses does not need to be even; he subsequently developed a cost-effective three-lens camera that is even better than a camera with four lenses (21). In the late 1970s, Lo also developed a continuous recording technique in which a moving slit aperture is used (22), thus avoiding use of the negative as an intermediate image carrier.

Other methods of autostereoscopy are the parallax barrier technique (23) and holography (14). In this article, we discuss 3D photography, physical principles of the lenticular system, and medical applications of the lenticular system and compare the lenticular system with holography.

■ THREE-DIMENSIONAL PHOTOGRAPHY AND LENTICULAR SCREENS

Okoshi (14) gives a good overview of all the techniques that have been explored for photographic recording of lenticular screen 3D photographic pictures. Koseki et al (24) have classified them into 10 different categories. All of the systems make use of one (moving camera) or multiple (multilens camera) objective lenses. The image recording is done on the lenticular screen directly or, most commonly, on negatives. In practice, the number of possibilities is limited because so-called keystone distortion (ie, a rectangle in the image scene becomes trapezoidal when the plane of the objective lens is no longer parallel to the plane of the

rectangle) must be avoided. Keystone-free images are obtained when the orientation of the plane of the objective lens remains unaltered during the recording of the 2D aspects. During the photographic printing process, the plane of the negative must also remain parallel to the plane of the lenticular screen and to that of the objective lens of the printer while the magnification factor is kept constant.

The angular shift between the two 2D aspects that the two different eyes perceive is 3° – 5° (larger angles exaggerate the stereoscopic effect), but the angular increment between adjacent 2D views is usually smaller (eg, 0.5° – 2°). This is because a lenticular system, with the requirement that the two adjacent 2D aspects be perceived by the two eyes, is too critical in terms of viewing distance. The number of separate 2D aspects recorded on the lenticular screen is determined by the number of lenses on the 3D camera. If the 2D views are computer generated, the number of 2D aspects is arbitrary. In practice, however, the transparent screens—with a lenticule width of 0.16 mm—record seven 2D aspects, whereas the opaque screens—with a lenticule width of 0.1 mm—record five 2D aspects. Moving slit cameras record only on lenticular screens directly and are of the single lens-moving camera type. They record an infinite number of 2D aspects.

■ PHYSICAL PRINCIPLES OF THE LENTICULAR SCREEN CONCEPT AND VISUAL PERCEPTION OF 3D LENTICULAR HARD COPY IMAGES

The modern microlenticular screen is a sandwich composed of a lenticular sheet and an image carrier (Fig 2), which normally is an opaque or transparent layer of photographic material.

In some types of lenticular systems, the image carrier is not a photographic emulsion but is printed separately and is laminated later beneath the lenticular sheet. This postlamination creates two problems. The first is that the lenticular screen used during recording may need a different pitch than the one that is laminated to the printed image carrier owing to shrinkage of the original film during processing. The second involves registration of the lenticular sheet with the printed image carrier in such a way that all lenticules are aligned with the zones of the underlying 2D aspect image grids. This problem makes the production process costly and vulnerable to errors of misalignment (25). In 1974, A. K. W. Lo filed a patent (26) describing a process that eliminates this problem by

and are normally referred to as "3D images" (despite their 2D character). Computer-based 2D aspects are composed of pixels in an image matrix. Therefore, when computer-based images are printed, this matrix must be mapped onto the image grid of the lenticular screen. In the layout example shown in Figure 5, the size of the matrix is the same as that of the image grid, but the matrix size may also be smaller, preferably twice as small to prevent undersampling by the number of available lenticules, which was 880 in the case of our sample image (Fig 6) from the Visible Human Male (27). In this manner, a coherent set of 2D aspects is recorded directly on film or generated and stored in a computer-readable form (graphics interchange format [GIF], tag image file format [TIFF], Silicon Graphics Inc [SGI], etc) (28) and then recorded on film. To generate our sample image (Fig 6), segmentation and surface rendering were used (29) because volume rendering (30) inherently creates transparency with an associated lack of stereoscopic effect (9).

■ MEDICAL APPLICATIONS OF THE LENTICULAR SYSTEM

With the establishment of tomographic imaging modalities (CT, magnetic resonance [MR] imaging) in the late 1970s, postprocessing techniques were developed to create 3D images (31), which have been used clinically over the past decade (32). However, these 3D images have been viewed primarily in a 2D fashion like a normal photograph of a 3D scene. It was thought that these images still lacked true depth, especially in the visualization of complex trauma (33) and vascular disease (34). Therefore, we supplied surgeons with images that we generated in a classic stereoscopic fashion (the Brewster technique).

Today, however, with the advent of the modern microlenticular system, it has become feasible to print these images in the form of autostereograms (35). Over the past 2 years, we have done so for selected 3D images to expose surgeons and radiologists to this new technology. They regard these hard copies as a great help in comprehending the spatial relationships (location, extent, approachability) between diseased and normal tissue in selected complicated cases. The primary reason why this technique is useful is that it removes the 2D ambiguity that still remains in the viewing of classic medical 3D images.

Because of the way we have used this medium (sending the data to a laboratory and receiving the results 1 week later), it has not yet been applicable in actual clinical practice. However, the medical applications of this technology have stimulated development of a cost-effective 3D digital photographic printer that can be placed in the hospital and thus provide a direct service. This printer takes high-resolution video images produced from a digital input, registers them automatically, and prints them in the correct direction onto the lenticular screen. This means that constraints of both time and price have been resolved, and thus lenticular hard copies will be available in the near future in a matter of minutes and at a material cost of less than \$2.50 a sheet (27.5 × 27.5 cm), provided that the volume of images processed per hospital is large enough.

An increase in the volume of images processed may well be stimulated by the growing production of 3D data sets in new medical applications such as rotational angiography, ultrasound, single photon emission CT, scanning electron microscopy, and confocal microscopy (36), in addition to the classic applications such as CT and MR imaging. There are also applications that have not yet been fully developed, such as computer design of drugs and laser scanning (eg, of the surface of a patient's face before surgery to allow computer simulation of the expected postoperative results). With the development of binocular microscopes and endoscopes (37), intraoperative photographs for documentation can now also be printed as microlenticular stereograms. Finally, we believe this technique will be useful in the future in the field of publishing for medical and scientific illustrations.

We have tested the lenticular system in most of the applications noted above, and our results have been exciting. Because of the difficulty and costs of reproducing such images for this article, we reproduced only one 3D image, an image of the knee reconstructed from the Visible Human Male slice data of the National Library of Medicine. This 3D hard copy (autostereogram) (Fig 6) demonstrates how useful the lenticular screen technique can be for educational and clinical purposes.

■ COMPARISON OF THE LENTICULAR SYSTEM WITH HOLOGRAPHY

Holography is a special photographic technique that was introduced by D. Gabor in 1948 (38). It is usually performed by recording the interference between a direct parallel laser beam

and a laser beam that is reflected from the object to be photographed. Relatively recently, holograms have been computer generated. As evidenced by the cover of the March 1984 issue of *National Geographic*, holograms can also be printed (39). The first computer-generated medical 3D hologram to be printed was a CT image of the spine on the cover of the November 1987 issue of *Diagnostic Imaging* (40).

Although many different types of holograms are possible, such as the cylindric or multiplex hologram (41), they have in common the ability to be viewed over a fairly wide angle. This is not the case with the microlenticular system, for which the viewing direction must be more or less perpendicular to the plane of the lenticular screen. Another advantage of holography is its greater stereoscopic fidelity. However, holography requires special lighting whereas lenticular systems do not. One of the most significant advantages of lenticular screen images over holograms is that a lenticular screen image can be painted in bright true colors (Fig 6). A hologram has either one specific color throughout (monochromatic) or multiple colors (those of the rainbow spectrum), which change as the hologram is tipped forward or backward. However, it is possible to use different parts of the visible spectrum for different parts of the image. Technically, it is also possible to make a full-color hologram, but this requires a red, green, and blue laser and the quality at the moment is still marginal.

Recently, a system for medical holography has been developed (42). The black-and-white films are transparent and are placed on special light boxes. Placing a small transparent projection screen in front of this type of hologram makes it possible to show a cross-sectional plane that can be moved forward or backward by the observer (43). Another viewing possibility is realized if one turns the film over and puts it back on the light box, thus reversing the viewing direction (eg, from anteroposterior to posteroanterior). Also, multimodality matching is possible by placing two films on top of each other, since the imaged objects remain transparent, although this inherent transparency impairs the stereoscopic effect, as mentioned above. Future extension of the use of lenticular screens in liquid crystal display (LCD) screens (44) and projection screens is not feasible for holography (45). With the advent of modern computer-assisted manufacturing techniques, it is becoming easier to manufacture microlenticular arrays. This should stimulate increasing use of this technology (46).

■ CONCLUSIONS

The microlenticular screen technique is an excellent and cost-effective way to present complex 3D full-color morphologic information to clinicians, especially in situations in which 3D workstations are not available and the use of special glasses or a viewing device is not desired (eg, the operating room). The lenticular technique overcomes the limited color capability and specialized lighting requirements of holography. The development of a cost-effective 3D digital printer will make the microlenticular system viable for clinical medical applications.

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Figure 6. Lenticular image shows a 3D reconstruction of the right knee of the male cadaver used in the Visible Human Project (27). The reconstruction was performed with the original tissue colors and shows the bones of the knee in relation to the muscles and superficial blood vessels. The ligaments are not shown. Best results are obtained when the image is viewed at a distance of approximately 50 cm in a viewing direction that is perpendicular to the lenticular sheet.