Title

True Three Dimensional Stereographic Display of 3D Reconstructed CT Scans of the Pelvis and Acetabulum

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Fractures of the acetabulum can cause the pelvis to shatter into a wide array of complex configurations which can be difficult to fully delineate preoperatively. In addition to plain radiography and standard computed tomography, technology now allows the reconstruction of magnetic resonance imaging (MRI) and computed tomography (CT) data into virtual objects; three dimensional (3D) representations of anatomy which exist only within the computer memory. Printouts and photographs of 3D reconstructions provide another level of anatomic information to the orthopaedic surgeon. However, current standard displays such as computer and video screens and photographic and radiographic film are all two dimensional (2D) modalities. Displaying 3D reconstructions in this standard 2D fashion, inescapably robs the images of up to one third of the information contained within them—all the true depth information which

is the essence of 3D. Shading techniques and perspective have both been utilized to simulate depth, but true depth is still lacking. Recently, the authors have begun using a technique of computerized 3D reconstruction and recording which provides a true 3D display of the reconstructed images. The resultant gain in image realism is profound, somewhat similar to hearing full stereo audiophonic recording compared to monophonic, or to seeing in color rather than black and white. The image generation and display process is a computerized mathematical adaptation of the photographic technique of stereophotography. Once in place, the technique is relatively simple to use and can be achieved in several ways with a minimum of additional hardware. Potential benefits lie in the method's ability to convey, in one 3D display, the true 3D, spatial anatomic configuration of the imaged pelvis. The methods described are common to those forming the fundamental basis for virtual reality imaging. Current users of some 3D reconstruction systems can now easily generate images which can be viewed with all of the depth information restored, into a true 3D display.

The purview of the orthopaedic surgeon is the skillful correction or improvement of abnormal anatomy. This is achieved through

thoughtful formulation and execution of a plan to alter the existing abnormality so as to return it to normal or to achieve some form which best restores function. This requires a thorough understanding not only of normal anatomy, but also of the specific pathologic alterations that exist in an individual patient. For most orthopaedic conditions, history, physical, and plain anteroposterior (AP) and lateral radiographic examinations provide more than enough information upon which to act. Fractures of the pelvis and acetabulae represent one area where these traditional modalities may not be sufficient.

The pelvis is a complex three dimensional (3D) object. When fractured, especially when the acetabulum is involved, it can assume a vast array of complex configurations. In such settings, history and physical exam may provide only minimal clues to the underlying configuration; therefore, radiological examination takes on a relatively greater level of importance. Often these studies provide the foundation upon which diagnoses and preoperative plans are built. The utility of each radiographic study depends upon how much and how readily information can be extracted from it and used to aid in the construction, in the surgeon's mind's eye, of a 3D understanding of that patient's specific internal anatomic spatial relationships. Since the choice of both the surgical approach and technique of internal fixation are very closely dependent on a correct assessment of fracture configuration, for pelvic and acetabular fractures it has become routine to obtain three to five different plain radiographs (AP, obturator and iliac oblique, inlet and outlet views) as well as a computed tomography (CT) scan preoperatively to help delineate fracture pattern and fragment orientation.[13,25]

The information provided by CT scans can be of great help in understanding the anatomy but the mental integration of a large set of individual slices into a single mind's eye image can prove to be difficult and error prone. A significant advance in the representation of this information is the development of so named 3D reconstructions, the computerized ability to stack the slices all back together, providing excellent images of the data that are one step closer to the actual anatomy. Unfortunately, computational abilities have outstripped standard display capabilities. CT data can exist as a 3D matrix within the computer memory, with all spatial relationships accurately recorded, however, this 3D array is then reduced to a two dimensional (2D) projection of the array on a flat computer screen or photograph, depriving the image of its depth.

In nonmedical technical fields, techniques have been and are being developed and refined for true 3D displays, the ultimate of which is the virtual reality environment.[2,3,6,8,14,17,18,23,24] The goal of the authors has been to develop and adapt these techniques to produce truly 3D displays of 3D reconstructed CT and magnetic resonance imaging (MRI) data. The expectation is that restoration (or maintenance) of all spatial information available in a scan will produce images one step closer to a true representation of the fractured acetabulum upon which the surgeon is preparing to operate, and will improve the efficiency and accuracy of the surgical improvement. Presented here are samples of digitally derived stereographs which can be viewed in 3D, and a description of a simple algorithm for production of stereo 3D images for those with existing 3D reconstruction platforms. The authors hope to promote an interest in this diagnostic tool among surgeons in order to fuel widespread development and availability of virtual reality, or near virtual reality, preoperative workstations.

DIMENSIONAL CLASSIFICATION

Currently a wide variety of radiological tests are available including plain films, digital radiography, tomograms, angiograms, ultrasonography, bone scans, MRI, CT, 3D reformatted CT, 3D reconstructed CT or MRI. The evolved terminology regarding them, however, makes this particular discussion

potentially confusing. For the purposes of this paper, these studies must be identified dimensionally. Both the number of dimensions provided by the display modality and the number of dimensions possessed by the object imaged are identified. For example, a painted portrait is a 2D representation of a 3D object. A sculpture is a 3D representation of a 3D object. However, a photograph of the Venus de Milo is merely a 2D representation of a 3D object.

Plain radiographs, therefore, are 2D projections of 3D objects. Perhaps counter intuitively, by this classification, ultrasonographs, tomograms and standard CT and MRI studies are all 2D projections of 2D objects—flat pictures of single voxel thick slices. Of course, the whole study contains the 3D information split up into the many sequential 2D projections of 2D images that make up the entire scan. CTs can be reformatted to yield 2D images of slices in different planes (2D projections of 2D images) or, more recently, they can be 3D reconstructed. CT and MRI 3D reconstructions are produced by mathematically stacking all the sequential slices back together into a 3D virtual object (one that doesn't actually physically exist) within the memory of the computer. The stunning images thus produced have demonstrated advantages over simple scans and are coming into increasingly wider use.[4,7,9,11,15,29] However, while these images are widely labeled 3D reconstructions, the standard modes of displaying them—computer screen, photographic film, video—are all 2D. This fundamentally restricts our visualization of them to 2D projections of 3D objects. At best, what can be seen is only representative, as are photographs of statuary from a museum trip. To overcome this limitation, several potential avenues exist for the generation of true 3D reconstructions of 3D objects.

BINOCULAR VISION

The ability to visually perceive the world in 3 spatial dimensions, while generally taken for granted, is not an intuitively obvious ac-
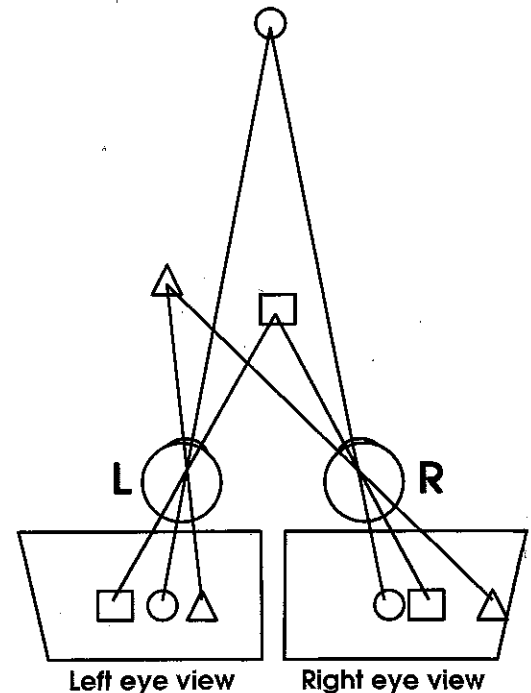

Fig 1. The horizontal offset of the 2 eyes gives viewed points and objects differing relative horizontal positions on each eye's retina. This shift in position from eye to eye is horizontal parallax and is responsible for depth perception. Note that no vertical shift or parallax is created by horizontal offset.

complishment. Great thinkers have pondered the puzzle: if with 1 eye we simply see 1 image of the world, with 2 eyes, why don't we see a double image of everything around us? Both Euclid and, later, Leonardo da Vinci recognized that separately each eye sees a slightly different image than the other.[16] However, it was not until 1838 that Sir Charles Wheatstone first published sketches demonstrating the nature of the differences and their significance to depth perception.[27]

It has been clearly established that left and right eye retinal images are fused by the visual cortex into a single stereoscopic 3D image.[20] It is the disparities between the left and right eye images that are processed and converted by the brain into depth information, providing 3 dimensionality (Fig 1).[1,20] Thus, with 2 single eye views of the

Fig 2. 3D multiplane lenticulars are created by vertically interleaving multiple sequential slightly offset images viewed through an overlaid array of cylindrical lenses. Interleaving causes significant losses of individual image data to create room for neighboring interleaves, diminishing resolution.
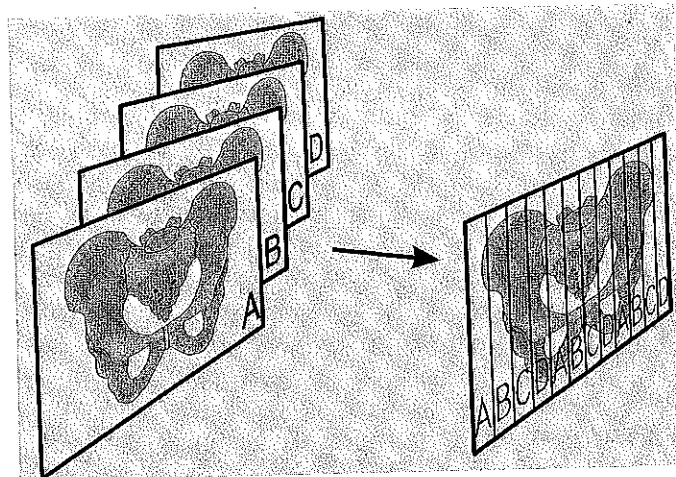
world one can easily perceive not only the horizontal and vertical, but also depth positions, attributes, and relationships of objects in space. Unfortunately, between 2–10% of individuals are so strongly dominant in 1 eye that they are not able to fully appreciate the 3D effect.[5] This may not be readily obvious to those of us so affected because a number of monocular cues, such as perspective, relative motion, overlap, and shading can all enhance and suggest depth.[20] Nevertheless, true depth perception results from stereopsis, as is quickly made apparent by simply looking around with 1 eye closed.

METHODS

Generation of a 3D display of CT and MRI data requires a selection of potential display modality, derivation of an algorithm for mathematically transforming the data matrix into images adapted to that display method, and implementation of the computational and physical requirements for creating the 3D images. Three major, distinct 3D display techniques currently exist: multiplanar interleaved lenticulars, holography, and variations on stereography.

Lenticulars

Most people have seen or possessed 1 of the 3D images or photographs that were once quite popular. Several variations exist. Typically, these images are produced by vertically interleaving 4 or more sequentially offset images of a scene or object (Fig 2). A flat lenticular

array of cylindrical lenses is then affixed to the composite image. The cylindrical lenslets are spaced in such a way that as the incident angle of gaze changes, only 1 of the 4 interleaves is viewable within each given angle of arc. Since the eyes are looking on the picture from different angles of incidence they see different interleave sets, effectively presenting each eye with a different image.

The major drawback with lenticulars is one of resolution. Because the final picture used is a composite, typically of 4 images, three quarters of each contributing perspective view must be discarded to make room for the 3 other interleave sets. Also, as the 3D effect is expanded with more interleaves the image resolution falls further. These factors, together with the need for off site processing, make lenticular images impractical for medical imaging.

Holography

A basic hologram is generated when a laser light beam is split, with 1 portion expanded and directed towards the object to be imaged and the other expanded and reflected towards the holographic film. As the object reflected beam and direct reflected beam reach the film, a light interference pattern is created by their phase differences, creating a holograph. Light transmitted or reflected from the holograph can recreate this light interference pattern, and thus, an image of the object. The pattern seen varies slightly with the angle of incident gaze so an observer's left and right eyes see slightly different images similar to what would be seen if looking at the real object.

Traditionally, an actual physical object must be used and placed into the imaging beams to generate a hologram. The process is time consuming and typically has a high production cost associated with each original image. Several groups are working to refine methods of digital laser holographic printing, to go directly from computer generated mathematical virtual objects to holograms, bypassing the object stage.[8] Holograms from CT data are being produced for commercial and research purposes on a small scale by, in essence, multiple exposure of a holographic plate with each individual CT slice, 1 at a time (Voxel Corp., Laguna Hills, CA). This time consuming process must be performed with highly specialized equipment at a commercial facility away from the scanning site. The images are troubled by fuzzy resolution and color fringing problems which hopefully will be overcome with further research.

A different holographic approach under development at the Massachusetts Institute of Technology may have promise but it requires extremely fast and large computers and is a method for real time digital holographic projection. The ultimate goal is production of dynamic color images which exist as volumes in space, viewable through 360°; at present this is not possible.[6] Even if the remaining obstacles are overcome, image production may be inextricably tied to very high end laser and computer equipment, limiting the availability and utility of this approach.

Stereography

The most widely adopted methods for both technical and nontechnical 3D image displays are various forms of stereography. Digital stereography and stereophotography are used routinely in a number of fields including geologic survey and cartography,[17] flight training and battle simulation,[23] light and scanning electron microscopy,[3,14,18] molecular modeling,[24] computer aided design, manufacturing,[23] and manned and unmanned space exploration.[17] They are beneficial anywhere that exacting photographic records are required, spatial calculations from stereophotogrammetry is performed, or depth information is required but unavailable from the 2D display.

The most rapid developments in stereographic imaging methods stem from its use as the foundation for virtual reality environments. Despite this, the production of 3D projections of 3D images in this way is not new, in fact

it dates back to 1839 shortly after the birth of photography. Photo and radiographic techniques of stereography involve the production of 2 separate whole images of a scene or object, each composed in such a fashion that separately they reproduce the views that a person's left eye and right eye would see if actually looking at that scene or object. The images are then simultaneously presented separately to the left and right eyes respectively and the scene is visualized as if it were really present in 3 dimensions.

Stereo imaging via stereo radiographs was even popular in medicine for a period. Its usefulness was limited, however, by the difficulty in producing good matched pairs, difficulty for some people in viewing them, and the necessary double radiation dose to the patient. The idea was sound and useful in some situations but implementation was limited by the technology at that time. Technological advances are expanding the medical use of stereography once again.[22,26]

With the advent of computer imaging it is possible to precisely generate stereographs of computer generated objects and scenes. Each new increase in computer speeds and capability allows real time creation of digital stereo images with objects of increasing complexity. Soon, the threshold of affordable computational power and speed for real-time virtual reality imaging of complex CT and MRI data sets will be crossed technologically. This should make it routinely possible for a surgeon to both see and interact with 3D computer generated representations of patients' anatomy on a preoperative workstation. It is these potential advantages that have fueled the authors' interest in stereography for 3D projection of the 3D images of CT and MRI reconstructions.

Algorithm

In stereo photography stereographs are created by 2 parallely aligned cameras or lenses separated by a calculated horizontal shift that approximates intraocular distance. This produces stereo images which differ only in their relative horizontal positions of homologous points within the imaged fields (horizontal parallax). Importantly, a pure horizontal shift produces only horizontal parallax, and no vertical parallax (Fig 1). The ability of human eyes to independently shift in the horizontal plane (converge at different angles) allows the retinal superimposition of homologous points as gaze wanders about the visual field, despite variable horizontal parallax (Fig. 1). No such eye shifting is possible to re-
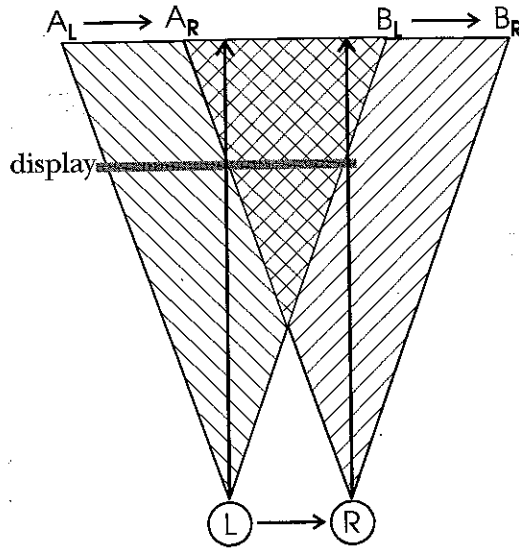
Fig 3. Computerized generation of stereo pairs by horizontal offset can cause significant side clipping due to shifting of the object out of the window of display. This causes partial loss of images and limitations on the 3D imaging area (crosshatched).

solve vertical parallax. A computer generated stereo pair algorithm must mathematically adhere to the same rules of image composition, creating appropriate horizontal parallax without vertical parallax. From a practical standpoint, however, the imaging region of the computer is restrained by the screen boundaries. Thus, a simple horizontal shift of observer viewpoint to generate the stereo image can cause significant side clipping of full frame images resulting in too much image loss or necessitating significant reduction in image size and consequent loss of resolution (Fig 3).

The seemingly obvious solution would be to follow this mathematical horizontal observer shift with an observer rotation to recenter the pelvis on the screen (Fig 4). The problem with this maneuver is that, the rotation brings some points on the object closer to the second observer position and moves some further away (Fig 5A). A conformance to the laws of physics then dictates that this simple rotation creates vertical parallax due to perspective and distorts the vertical homology of the images. A number of solutions to this dilemma have been proposed.[10] The simplest was achieved by recognizing that by somewhat ignoring that law of physics, perspective can be eliminated, and thus its consequence, ver-

tical parallax (Fig 5B). While perspective cannot be eliminated in the real world, in a mathematically created virtual world it is accomplished with relative ease by rendering the images as parallel projections, and actually simplifies the equations upon which image generation is based (Fig 6A–B).

The broad use of nonperspective rendering in the generation of virtual scenes has been correctly criticized. Typically, virtual environments have depths of field that are significant relative to object sizes. The lack of monocular perspective depth cues visually conflicts with the concurrent binocular size and depth information represented, causing apparent image and object distortion and loss of realism. The authors have found, however, that when used for pelvic imaging (single anatomic figures of complex shape and limited field depth), the nonperspective distortion goes virtually unnoticed. This proves to be quite fortuitous, because it then allows some already in place systems, designed for standard 2D projection of 3D reconstructions, to be readily used for the production of 3D projections of 3D stereo pairs of very acceptable quality, as will be seen.
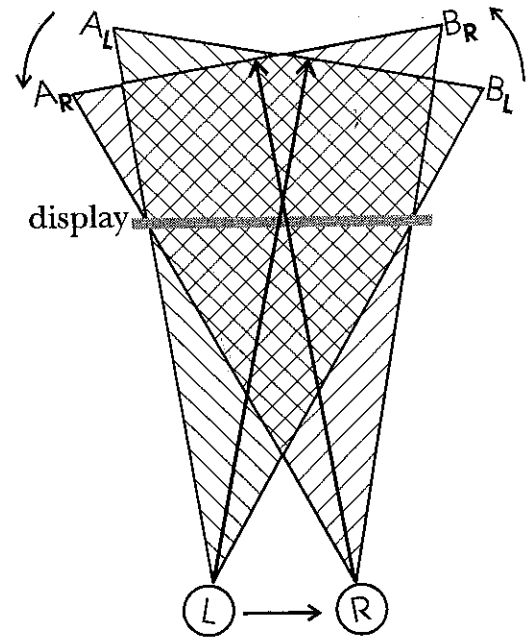

Fig 4. Rotation to recenter the offset view or rotation of the object can eliminate side clipping and increase the 3D imaging area size relative to screen size.
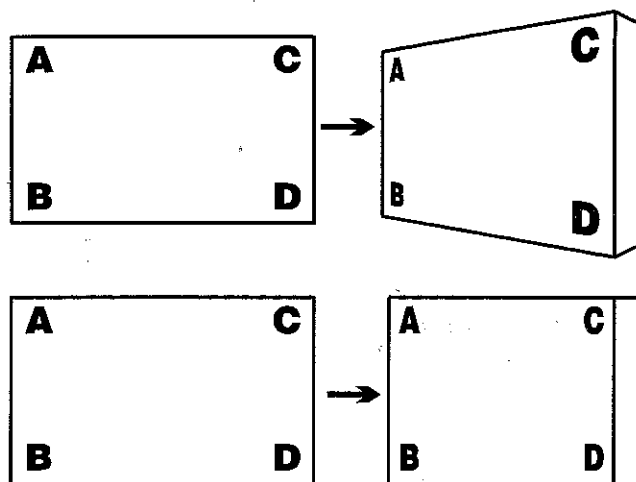
Fig 5A–B. (A) Simple rotation causes vertical parallax due to perspective distortion. Segments AB and CD change vertical size and position in addition to the horizontal change. (B) Parallel projection rendering of rotated images causes horizontal parallax but eliminates vertical parallax.

Image Production

Continuously acquired 3–10 mm CT sections were obtained of the studied pelvises using a GE 9800 Scanner (Milwaukee, WI). The data were recorded onto magnetic tape or optical disc for
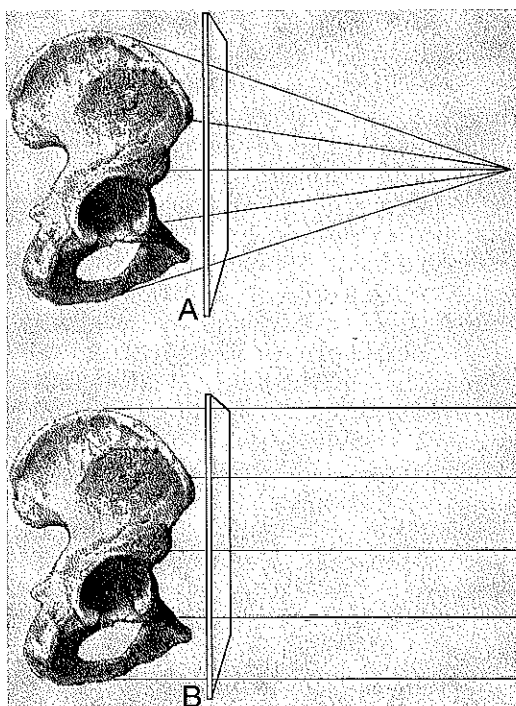
Fig 6A–B. Illustration of (A) perspective versus (B) parallel method of rendering of objects into images.

storage and transfer. Initial images were generated by simple surface rendering of perspective views utilizing depth shading on a DEC Micro VAX II. Size and side clipping limitations were initially addressed with rotational recentering of objects. However, perspective generated vertical parallax distortions significantly degraded the stereo images. Once this became apparent the program was ultimately rewritten, eliminating perspective by performing parallel projection renderings. Excellent discussions of the mathematics and geometry of the various imaging paradigms used are presented by Hodges and McAllister[10] and by Baker.[2] In addition to creating better full frame stereo images, computational times were reduced. Initial images were quite crude however, and suffered from significant resolution as well as edge artifacts, greatly limiting their utility. Subsequently, the authors became aware of several companies developing commercial CT and MRI reconstruction systems who, purely for reasons of computational economy and increased speed, fortuitously chose to parallel render nonperspective 2D projections of 3D images. In 1989, a Sun Systems SPARCserver 470 workstation with an ISG Allegro graphics engine (ISG Technologies, Mississauga, Ontario, Canada) dedicated to 3D CT and MRI reconstruction was acquired by the author's institution. The system was easily adapted for the production of 3D projections of 3D images, taking advantage of its superior computational speed, resolution, shading, and edge enhancement capabilities.

Currently, CT scan data is reconstructed into

separate pelvic, femoral, and sacral 3D objects in a semiautomated fashion using bone thresholds and seeding of individual slice volumes of interest. The reconstructed objects are sized, rotated, and cut away as desired. Parallel projection surface renderings are created from viewpoints of interest and stereo images are automatically generated utilizing 7° Y axis object rotation disparity.

Users of this or other 3D reconstruction platforms that use parallel projections can manually create similar stereopairs. After reconstructing the CT or MRI data into 3D objects in the standard fashion, stereopairs are generated by manipulating the objects into a position of interest parallel rendering and recording this view as the left eye image. Maintaining the same vertical position and magnification, the objects are then concomitantly rotated in the horizontal plane 7° clockwise around a common axis, rendered, and recorded. The image thus created becomes the companion right eye image to the first. A similarly created sequence of 6° or 7° rotations can be viewed as an overlapping series of stereo images.

Viewing stereo images

The stereo images may be viewed in a variety of ways. The author's software and hardware configuration modifications allow direct on-screen viewing of 3D projections of 3D images. Stereopairs may also be recorded on 35 mm slide film for future presentation, and printed as hardcopy stereographs for patients' charts and film jackets. Additionally, for some cases images are recorded to videotape via digital to analog conversion by genlock and frame sequential, time multiplexed recording on 3/4 inch U-Matic, Betacam, or VHS for 3D video presentation.

Hardcopy stereo images are output directly from the computer to a high resolution color printer as shown in Fig 9A–B. For versatility, the images shown are arranged as stereo triptychs, left image |right image| left image, so that the first and second of the 3 make a left-right divergent stereo pair and the second and third of the 3 make a right-left convergent stereo pair. They can be viewed with the use of a simple, hand held, binocular divergent stereo magnifier (American Optical, Southbridge, MA; Reel 3D Enterprises, Culver City, CA), or by the technique of "free viewing" with the naked eye.

To use a binocular divergent magnifier, one holds the images approximately 6–8 inches away and centers on the dividing line between the first and second images (left and right view)

of the 3 in the triptych. The lenses are pitched in such a way that they magnify and direct their respective eyes' gaze to their separate respective images. Each eye sees a different but appropriately disparate image that the brain interprets as a 2 eye view of a single 3D object.

Free viewing uses no devices other than one's eyes and can be accomplished in 1 of 2 ways; either through divergence or convergence. The method requires one to allow dissociation of normal vergence and accommodation and like any new skill may require some practice.

In divergence viewing, the images are held at a distance of 10 to 14 inches, with the gaze centered on the dividing line between the first and second images of the triptych. By relaxing one's gaze (reducing eye convergence) as if looking off into the far distance, the images will become doubled and then begin to overlie one another. Relaxing of gaze continues until the images exactly overlie each other and fuse into 1 image. If this gaze is maintained natural accommodation will occur and the 3D projection of the 3D image will pop into focus. The 3D effect is achieved because the left eye is centered on the first (left view) image, and the right eye is centered on the second (right view) image (Fig 7).

Convergence viewing is accomplished in much the same way but uses the rightmost pair of the triptych: With the images again 10–14 inches away, gazing at the dividing line between the second and third images, the eyes are crossed slightly. The crossed gaze directs the right eye at the second (right view) image and the left eye at the third (left view) image (Fig 7). Very little crossing is necessary to bring the 2 images to overlie. Once they overlap exactly they will fuse and focus relatively quickly as natural accommodation takes over. The 3D projection of the 3D images can then be visually explored since both convergence and accommodation become "locked on" to their targets.

With time an easy comfortable viewing technique, either convergent or divergent, can be established. Subsequently, images generated can be printed just as pairs, either left-right for divergent viewers or right-left for convergent viewers.

For presentations to larger audiences, the authors have utilized the technique of simultaneously projecting exactly overlying, orthogonally polarized left and right images. Each is separately projected through a linear polarizing filter, rotated 90° perpendicular to the other onto a silver surface projection screen (Wonderlite, Da-lite Corp.,
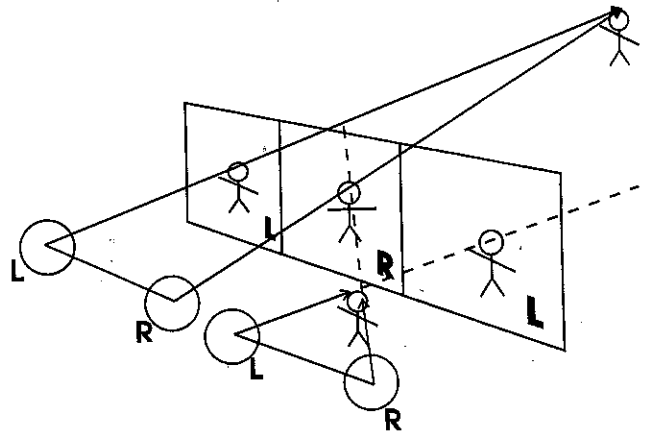
Fig 7. Divergent and convergent stereo pairs can be combined into a stereotriptych. The leftmost pair is viewed divergently, or the rightmost convergently, to present separate images to each eye.

Warsaw, IN; Silver 400, Stewart Screens, Torrance, CA). When inexpensive, similarly aligned, polarizing 3D glasses (Polaroid Corp.) are worn by audience members, only the correspondingly polarized left or right eye image is visible to the viewer's eye (Fig 8). In this fashion, the authors have successfully projected 14 foot full color full 3D projections of 3D images of pelvic and acetabular fractures to large audiences. Care must be taken in the preparation of such presentations however, since exact size and vertical alignment is critical to comfortable audience viewing. Additionally, for large projections image disparities of 4° or 5° more closely reproduce size and depth relationships.

Desk Top Virtual Reality

At our computer graphics workstation, onscreen production time takes a few seconds per image. Thus, only near real time manipulation of the images is possible. The complexity of these images and textures is such that super computer or near super computer levels of computational speed are required to accomplish real time manipulations in 3D projections of 3D images.[12]

With each advance in computational power and speed, the possibility of affordable, dynamic, real time, desktop, or immersion virtual reality explorations of these objects approaches. Nevertheless, excellent static images can be viewed in 3D projection of 3D images as they are produced directly on the computer screen.

Using a simple software routine, the computer display toggles back and forth between the computer generated left and right eye images at a very high speed. Special hardware driven glasses worn by the viewer, which are comprised of left and right eye liquid crystal windows (3D TV Corp. and Stereographics Corp., San Rafael, CA), are electronically shuttered at the same rate. At any given instant, either only the left eye window is open and the left eye image appears on the computer screen, or only the right eye window is open and the right eye image is on the computer screen. This time multiplexing takes place at a high enough rate of speed that visual persistence prevents one from noticing that the 3D projection of the 3D image seen is made up of separate left and right still images that flicker quickly, and the visual cortex sees a

Fig 8. Left and right images can be projected on top of each other onto a silvered screen surface through separate polarizing lenses rotated 90° out of phase to each other. An audience wearing similarly aligned polarized glasses sees only the left image with the left eye and only the right image with the right eye.
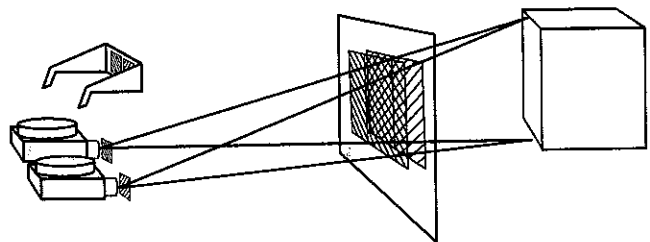
3D object. (Tektronix Inc., Beaverton, OR, also offers large liquid crystal diode windows for the computer screen that dynamically polarize to achieve a similar effect).

Once generated, the images can also easily be transferred digitally to any PC computer with a viewing program and the liquid crystal diode glasses. Images may also be saved and displayed in 3D projections of 3D images on a standard television by recording the images in a field sequential fashion onto standard videotape. A time multiplexing device interlaces the left and right images from the computer into separate scan raster fields of the video frames. When the videotape is played back on a standard VCR, the left and right eye images again flicker quickly on the screen and a similar hardware device (3D TV Corp., San Rafael, CA) connected to the video out port is able to drive the liquid crystal glasses. Viewing in these ways is limited only by the number of pairs of liquid crystal diode glasses available and the size of the computer or television screen.

RESULTS

Stereo images of 3D projections of 3D images produced in this fashion are quite striking (Fig 9A–B). Plain radiographs and CT slices of the same patient are provided for comparison (Fig 10A–B). The imaging software is configured to allow the automatic creation of stereopairs, so a complete set of hard copy stereographs of 3D projections of 3D images takes only a few minutes longer to generate and print than nonstereo 2D projections of 3D images. The average production time is 30–40 minutes after scanning and transfer of the data to the workstation. 35mm slide production adds only the amount of time it takes to shoot and process the slides. 3D video recording presently adds from 20–30 additional minutes due to a software limitation that when resolved will instead add only a few minutes to production time. All images can be obtained in final form on the day of scanning.

Several advantages to these stereo images were recognized. Since the 3D display is an optical superimposition of 2 images, the signal to noise ratio is benefited by averaging out random noise within the individual images, increasing clarity.[19] Also, apparent resolution is increased due to the combined contributions of different left and right view pixel paths along each line or edge that has any Z axis component. It has been demonstrated that visual explorations are characterized by moment to moment visual cortical heightening of percepts from center objects of interest and suppression of attention to surround regions or objects.[19,20,21] These images' ability to allow depth related visual separation of fracture fragments or regions of interest from the background appears to amplify or facilitate this effect, enhancing edge and surface detection. It has also been previously established that binocular visualizations increase both efficiency and accuracy of depth relationship determinations.[28] Especially for complex fractures, these techniques of stereographic imaging of CT data more readily and accurately convey anatomic relationships and fracture configurations than do their 2D projections of 3D image counterparts. This increased 3D understanding facilitates the conceptualization and formulation of preoperative plans and contributes to choice of surgical approach.

CONCLUSION

The evolution of computational power and speed now achievable in computer workstations opened the door for advanced digital processing of medical images. Previously impractical manipulations of large data sets, such as those acquired through CT and MRI scanning, can now be efficiently performed. One of the greatest advantages is that following a single acquisition the data can be reprocessed and represented any number of ways without exposing the patient to any additional radiation. Secondly, with relative automation in scanning, the format of final image display has become primarily a function of the mathematical transforms which are applied to the data, rather than of how the data set is acquired.

So named 3D reconstructions of CT and MRI data have provided very useful images
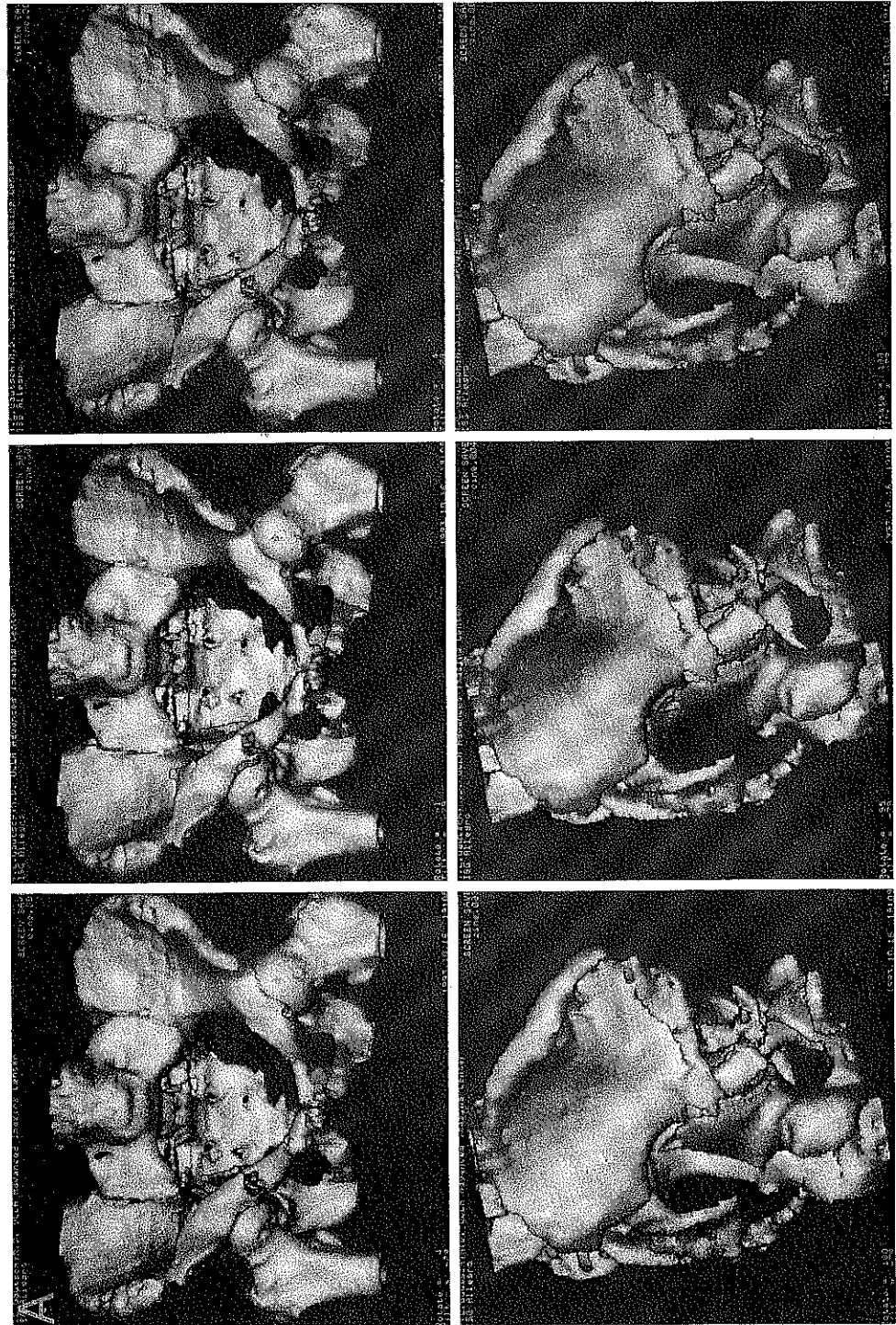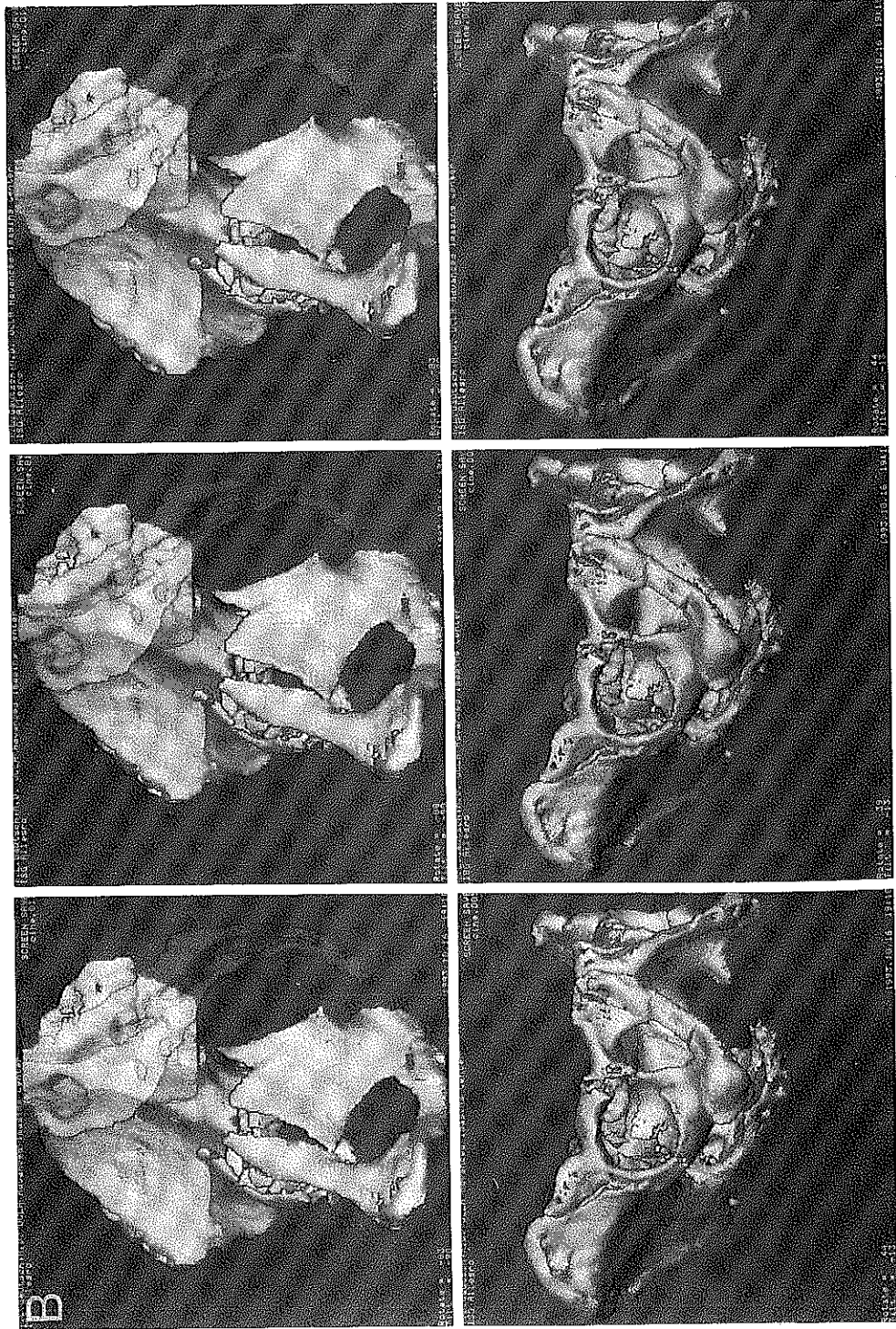
Fig 9A–B. Examples of 3D reconstruction of Figure 10 CT scan, presented as digital stereo triptychs which can be viewed 3 dimensionally, restoring all depth information (see text).
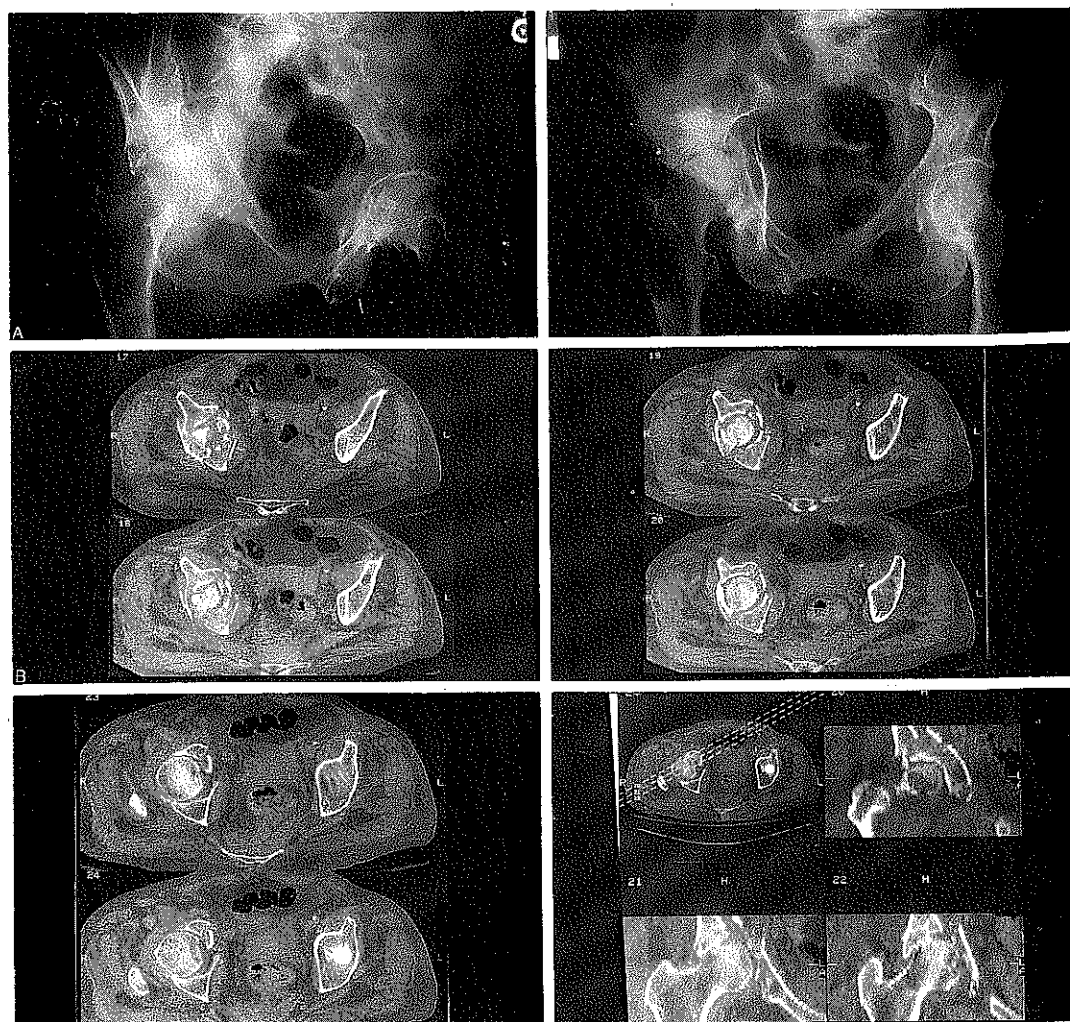
Fig 10A–B. (A) Plain radiographs of an acute acetabular fracture. (B) Select CT slices from same patient.

for the delineation of fractured pelvic and acetabular anatomy but, trapped within standard 2 dimensional displays they are stripped of most of the depth information that exists within them. Utilizing computerized techniques to create precise stereographs of such images allows the retention of maximal clarity and resolution of the images individually and provides greater utilization of the spatial information contained in the CT data. Stereoviewing allows each image to exert a profound synergistic effect upon the other. Realism, apparent resolution, and image clarity are increased, the

images can be explored not only horizontally and vertically but also at varying depth, and higher visual cortical processing of the images occurs. Altogether, these dramatically improve one's ability to recognize the true orientations and relative positions of fracture fragments and planes which otherwise tend to meld or mask each other on the 2D images.

This paper explores and demonstrates simple techniques for the computer generation of stereo images for 3D displays of 3D reconstructed CT scans as applied to fractures of the pelvis and acetabulae. The

technique can just as easily be applied to any CT or MRI scanned region with similar result. As described, it can be accomplished with relatively short production time on a variety of existing standard reconstruction systems. Several methods can be used for viewing separate from the generating system and implementation requires a minimum of additional time, cost, and hardware.

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