

Volumetric depth peeling for medical image display

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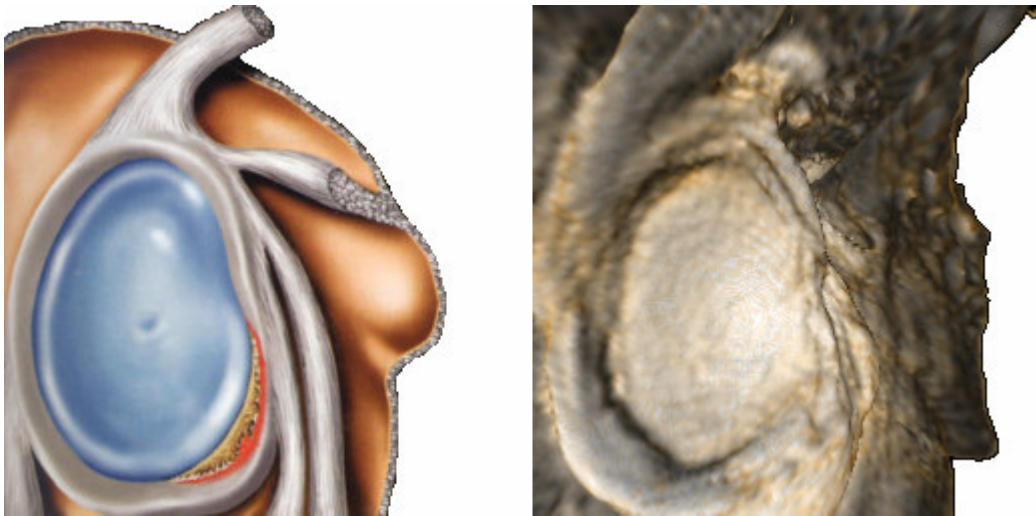


Figure 1: Shoulder Socket: Cutaway illustration from a textbook³¹ compared with volumetric depth peeling

ABSTRACT

Volumetric depth peeling (VDP) is an extension to volume rendering that enables display of otherwise occluded features in volume data sets. VDP decouples occlusion calculation from the volume rendering transfer function, enabling independent optimization of settings for rendering and occlusion. The algorithm is flexible enough to handle multiple regions occluding the object of interest, as well as object self-occlusion, and requires no pre-segmentation of the data set. VDP was developed as an improvement for virtual arthroscopy for the diagnosis of shoulder-joint trauma, and has been generalized for use in other simple and complex joints, and to enable non-invasive urology studies. In virtual arthroscopy, the surfaces in the joints often occlude each other, allowing limited viewpoints from which to evaluate these surfaces. In urology studies, the physician would like to position the virtual camera outside the kidney collecting system and see inside it. By rendering invisible all voxels between the observer's point of view and objects of interest, VDP enables viewing from unconstrained positions. In essence, VDP can be viewed as a technique for automatically defining an optimal data- and task-dependent clipping surface. Radiologists using VDP display have been able to perform evaluations of pathologies more easily and more rapidly than with clinical arthroscopy, standard volume rendering, or standard MRI/CT slice viewing.

Keywords: visualization in medicine, applications of volume graphics and volume visualization, view-dependent visualization, volume rendering

1. INTRODUCTION

3D display of medical data sets is an increasingly useful tool. Viewing 3D reconstructions of objects from Magnetic Resonance Imaging (MRI) and Computerized Tomography (CT) data is more natural and intuitive than mentally reconstructing these objects from orthogonal slices of the data, especially with the increase in the size of datasets due to ever-increasing scanner resolutions. When displaying such data sets using volume rendering, appropriate selection of the transfer function is critical for determining which features of the data will be displayed. For applications such as *virtual arthroscopy* (VA), how-

ever, even a careful selection of an appropriate transfer function is not sufficient to display entire objects of interest within a joint from a single viewpoint. In VA, due to the close proximity of surfaces in a joint, radiologist colleagues have found existing methods lacking for obtaining desired views of features of interest. *Volumetric depth peeling* (VDP) was developed to enable radiologists to obtain views exterior to the space between the bone and cartilage surfaces (“joint space”) for viewing entire areas of interest. Such views are impossible using standard volume rendering because the surfaces occlude each other from viewpoints outside the joint space. Radiologist colleagues also found a similar problem when using standard volume rendering for *virtual urography* (VU) studies in which the physician wishes to obtain views of the interior of the kidney collecting system (a sack called the renal pelvis, the ureter, and the bladder). In this case, a view from outside the kidney collecting system showing the interior is impossible to obtain using standard volume rendering, as the outer surface occludes the inner volume. VDP enables such views.

VDP extends standard volume rendering by automatically culling occluding voxels between the viewpoint and the features of interest, enabling unobstructed views of entire regions within the structure being examined. For VA, such views closely match standard textbook illustrations of joint surfaces (Figure 1) that are not possible even with clinical arthroscopy.

This paper is organized as follows: Section 2 describes previous work in volume rendering, depth peeling, and medical applications. Section 3 describes the motivating problems of VA and VU. Section 4 describes the VDP technique. Section 5 gives results of applying VDP to VA of a shoulder joint. Section 6 gives a summary and conclusions, and Section 7 presents future work.

2. PREVIOUS WORK

2.1 Volume rendering

Interactive volume rendering has had a long history since its first description.²² Kruger and Westermann describe hardware-accelerated volume rendering²¹ and Hadwiger et. al. show how to perform rapid multi-technique rendering of pre-segmented volumetric data sets on commodity graphics hardware.¹¹ Occlusion problems encountered when viewing entire volumes require classification and selection of which portions of the data to display.

The most general method of classification is specifying a transfer function to determine the color and opacity of voxels in the volume. The transfer function can be set to display isosurfaces in volume data.^{3, 23, 27} Recent research on volume rendering has focused on the design of complex transfer functions. Interactive^{17, 19} and automatic²⁰ techniques have been developed for the construction of multidimensional transfer functions that incorporate first and second derivatives to define surfaces.^{13, 18} Such work has led to an algorithm to automatically estimate opacity transfer functions to display tissue interfaces in noisy 3D ultrasound data.¹⁴ A parallel-coordinates interface that enables the user to efficiently search the large-dimensional parameter space, keeping track of the most effective settings and indicating nearby likely candidates is described by Tory et. al.³³ VDP integrates well with such work, as it determines which portions of the volume to cull independently from the transfer function definition, retaining the full range of transfer function control.

When viewing volume data, unimportant portions of the volume often occlude areas of interest. A technique for view-dependent transparency, which aims to automatically produce translucent surfaces similar to technical illustrations, is described by Diepstraten et. al.⁵ In a later work, techniques for automatically producing breakaway and cutaway illustrations of nested surfaces are described⁶. These illustrations remove portions of geometry that occlude the interior surfaces as opposed to rendering those portions as a translucent material. Most relevant to the VA problem is the work of Viola et. al.,³⁴ which produces importance-driven volume rendering that highlights features of interest and automatically subdues the display of occluding volumes using one of several possible techniques. These techniques are effective for pre-segmented volumes in which there exists a hierarchy of importance among objects. The problem of accelerating volume segmentation while rendering using graphics hardware has also been addressed.³⁰ VDP is designed for rapid operation in non-segmented data, as it is designed to aid physicians in rapidly diagnosing pathology, and does not require any pre-selection of importance criteria.

2.2 Depth peeling

Depth peeling is a framebuffer-based technique that can achieve order-independent transparency when rendering polygons.^{4, 8, 24} Depth peeling techniques have been extended to texture-based volume rendering of isosurfaces, originating the term *volumetric depth peeling*.³⁸ The implementation of VDP described in this paper borrows conceptually from these techniques, but is extended to the more general case of ray-based volume rendering, retaining full transfer function control (not just isosurfaces), therefore enabling the full range of volumetric effects to be applied (including effects that simulate directionally-illuminated surface rendering).

2.3 Medical applications

Volume rendering has been demonstrated to improve effectiveness in clinical settings compared to 2D and 3D views on film.^{12, 39} A volume-rendering-based interactive virtual colonoscopy navigation system is undergoing clinical validation.³⁵ A

combined surface and volume rendering approach for virtual colonoscopy that also indicates which region of the surface have been surveyed and which have not yet been examined has been described.¹⁶ Volume visualization systems have also been used for the study of aortic aneurysms.³² The feasibility of 3D rendering of joint surfaces and pathology using MRI and CT data sets has been demonstrated by several authors.^{1, 29, 36, 37} Such techniques provide real-time interaction and evaluation of joints for VA. However, this evaluation of joint surfaces is constrained to views within the joint space, as is the case in conventional arthroscopy. Fielding et. al. describe a system for color coding hand-segmented bladder walls by thickness for tumor detection,⁹ a task similar to that of VU. VDP enables each of these techniques to make use of more general viewpoints without requiring segmentation of the objects of interest.

3. ARTHROSCOPY AND UROGRAPHY

3.1 Clinical arthroscopy

Arthroscopy is the process of inserting an arthroscope (a small camera) into a joint through an incision in the skin, enabling viewing of the interior of the joint (Figure 2). Arthroscopy is useful for diagnosis of derangements within the joint and for performing surgery to treat such derangements. Arthroscopy is an expensive, invasive procedure that requires skilful manipulation of arthroscopic tools confined within the cramped spaces within joints. For pre- and post-operative diagnosis of joint derangements, it is less invasive to view Magnetic Resonance Images (MRI) of the joint.



Figure 2: Arthroscopy

3.2 MRI slice viewing

MRI images showing tissue densities provide an alternate method to display joint surfaces. By viewing slices of MRI data along the three orthogonal axes (Figure 3), clinicians can diagnose joint pathologies without the use of invasive arthroscopic procedures. Often, a contrast agent is injected into the joint to aid in diagnosis. Although joint pathologies can be determined from these images, diagnosis requires tedious manual selection of slices and a difficult mental reconstruction of 3D structures from slices along one axis, correlated with features along the other two axes. *Virtual arthroscopy* (VA) enables real-time evaluation of joint surfaces in 3D, removing this tedious slice manipulation and difficult 3D mental reconstruction.

3.3 Virtual arthroscopy

VA is the 3D rendering of joint surfaces from MRI or Computerized Tomography (CT) data sets for diagnosis of joint pathologies. Commercial systems such as the Siemens Syngo software running on the Leonardo workstation use standard volume rendering to enable VA flythroughs. With this flythrough system, the user can position the virtual camera in the joint space and move to obtain views similar to those obtained in clinical arthroscopy (Figure 4). Although it is non-invasive and requires no surgery, this approach shares the limitation of real arthroscopy: the virtual camera is confined within the joint space. To render the surfaces, the

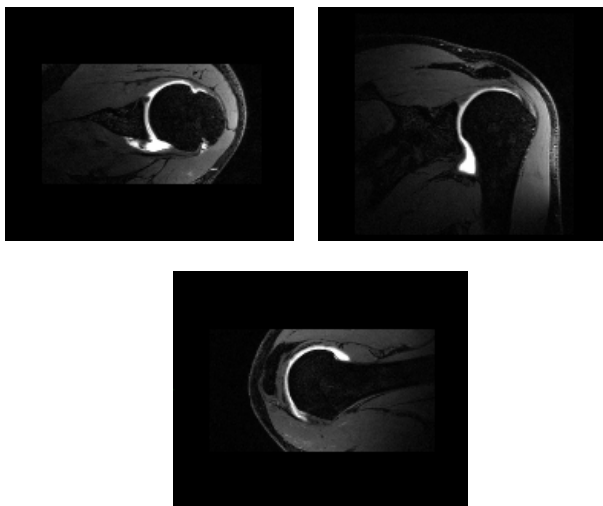


Figure 3: Shoulder: Three orthogonal MRI slices

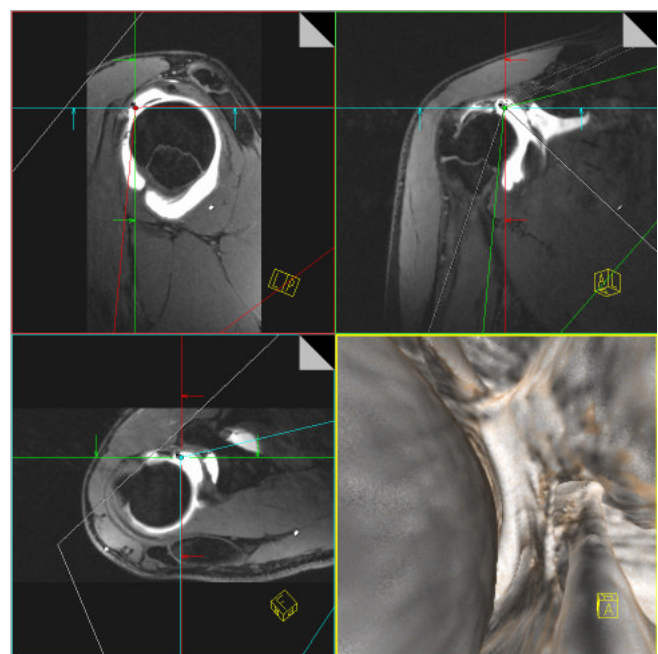


Figure 4: Shoulder: VA flythrough on Siemens Leonardo Workstation, illustrating a constrained viewpoint

transfer function of the volume rendering is set to render voxels within the range of values of the surfaces in the joint. Placing the camera outside of the joint space results in the surfaces occluding each other (Figure 5).

Because of this limitation, the clinician must evaluate the joint surfaces from viewpoints at extreme angles or very close to the surface, much like evaluating the surface of the hand with the palm touching the tip of the nose. This restriction necessitates tedious maneuvering of the virtual camera to find the best available positions from which to evaluate the surface and requires a mental reconstruction of the surface from these limited vantage points. Standard VA thus adds the burden of navigating the joint to the task of evaluating the images for pathology. VDP was developed at the request of radiologists to enable unconstrained placement of the virtual camera for unobstructed views of entire areas of interest by automatically culling occluding voxels between the viewpoint and the far side of the joint space. VDP provides views resembling textbook cutaways, enabling rapid surveying of the joint for pathology (Figure 1).

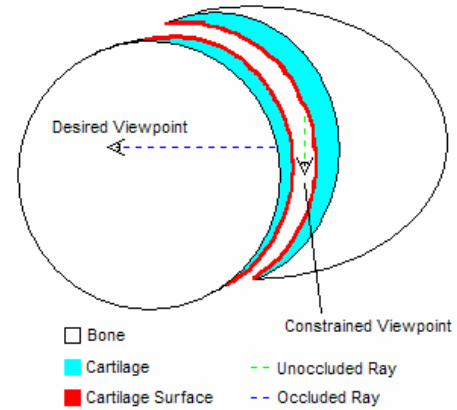


Figure 5: Shoulder Joint Schematic

3.4 Endoscopic uteroscopy

In endoscopic uteroscopy, an endoscope (a small camera, similar to that used in arthroscopy) is used to examine the kidney collecting system for tumors and stones. This procedure is costly, and can be very uncomfortable for the patient. It is also difficult to maneuver the endoscope into the multiple renal calyces (portions of the kidney urine passes through). Due to these drawbacks, physicians routinely view CT images of the urinary system in a technique called CT urography.

3.5 CT urography

In CT urography,^{2, 10, 25, 26} a contrast agent that appears very bright in CT images is injected into the urinary system of the patient and concentrated by the kidney which excretes it into the renal collecting system. The contrast between the agent and the tissue of the collecting system enables the physician to view CT slices to diagnose tumors, much like the technique of MRI slice viewing for diagnosing joint defects. CT slice viewing therefore suffers from similar drawbacks: tedious manual selection of slices and correlation with features in other slices to mentally reconstruct 3D features. Coronal maximum intensity projection images are also used, however in this case the physician is restricted to viewing from this projection. Collaborating physicians feel that multiple projections and opacity control are critical to enable *virtual urography* (VU) for improving upon CT urography.

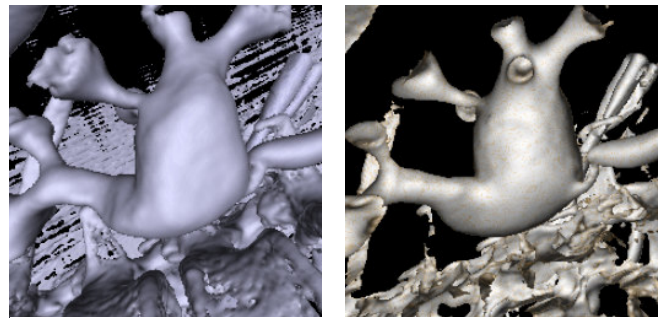


Figure 6: Renal Pelvis: Standard volume rendering of the exterior vs. VDP rendering of the interior.

3.6 Virtual urography

To perform VU, the physician would like to be able to obtain views of the interior of the urinary system (the renal pelvis, ureter, and bladder) from both inside and outside these structures. By using VDP, the physician can obtain views of the interior from outside these structures that are not possible using standard volume rendering (Figure 6).

4. VOLUMETRIC DEPTH PEELING

4.1 Description of algorithm

VDP is an extension to the standard volume rendering algorithm that gives users the ability to see through occluding material to the area of interest. In MRI images of joints, the contrast agent defining the joint space is brighter than the cartilage surface of interest and the clinician usually wishes to see the second surface through the first (Figure 7). The resulting threshold-based second-surface algorithm is:

```

reached_threshold = false;
while (traversing_ray) {
    if (!reached_threshold) {
        if (current_value >= threshold) {
            accumulated_opacity = 0;
            accumulated_color = 0;
            reached_threshold = true;
        }
    }
    do_normal_volume_rendering();
}

```

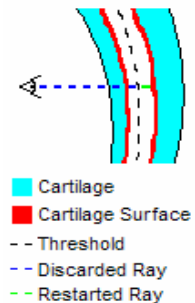


Figure 7: VDP diagram

The result of applying this algorithm to an MRI of an elbow joint can be seen in Figure 8. VDP can also render features of interest in joints such as wrists which have multiple occluding layers by choosing to render the third, fourth, etc. surface, or by rendering the last surface encountered, rather than the second (Figure 9). VDP is a simple addition to the volume rendering algorithm that enables rendering invisible all material between the observer's viewpoint and the feature that the observer wishes to see. VDP was initially developed for surface rendering of medical datasets. However, full transfer function flexibility and control is available. VDP has been used to render images of an aneurysm, complete with transfer function control of volumetric transparency (Figure 10), and is compatible with all transfer function effects, such as non-photorealistic rendering techniques.⁷ Using VDP with VA and VU, all of the accumulated color and opacity between the viewpoint and the surface of interest is generally discarded. However, this approach can be modified. By keeping some of the accumulated color and opacity, interesting transparency effects can be created (Figure 11). Note that the near and far surfaces are the same type of material from the same object, but are treated differently based on whether they are the near or far surface, enabling different transfer functions to be used for each. Using VDP, rays which do not get culled can be handled in two ways. They can be discarded to remove distraction, or rendered with a transfer function to provide context (Figure 12). VDP of CT scans of bone fractures, where there is no contrast dye and the intensity of the volume between the bones is lower than that of the bones, has also been successful (Figure 13). VDP was developed for medical imaging, but is directly applicable for viewing non-medical data, such as the engine block seen in Figure 12.

In summary, the VDP algorithm exhibits the following attributes:

- Simple addition to current volume rendering systems
- Requires no pre-segmentation
- Handles single, multiple, and self-occlusion
- Can discard or modulate accumulated color and opacity
- Can discard or display non-culled rays
- Independent of transfer function definition, enabling full range of transfer function effects
- Developed for medical applications, but generalizes to other volume data sets

4.2 Comparison with alternative methods

The remainder of the paper concentrates on VA and VU, using the simple threshold based method to render the second surface, with no transparency effects. Note that in these cases, determining the appropriate threshold is accomplished by setting the appropriate transfer function, as the threshold will be epsilon higher than the highest value included in the transfer function of the material of interest.

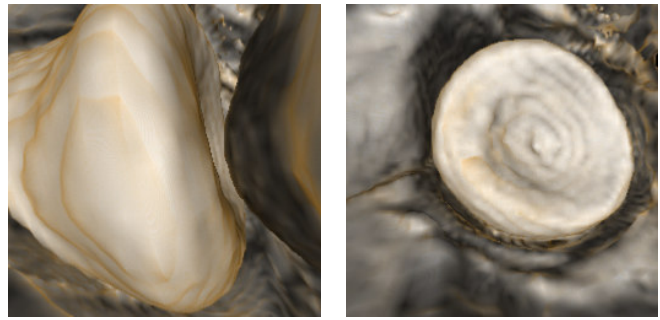


Figure 8: Elbow: Constrained view vs. view using VDP

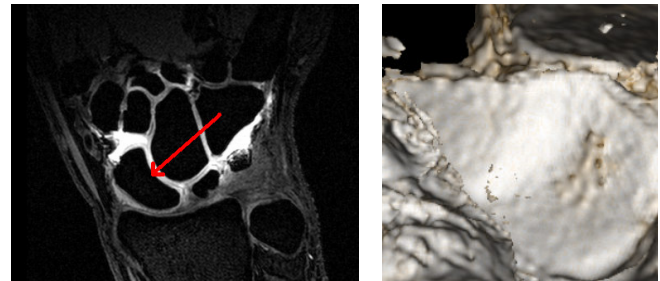


Figure 9: Wrist: VDP used to see through multiple occluding layers

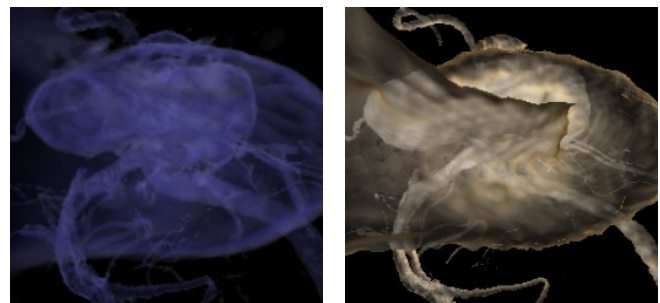


Figure 10: Aneurysm: Standard volume rendering with transparency vs. VDP with transparency

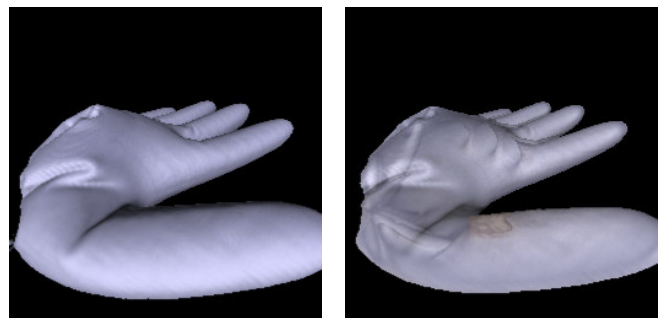


Figure 11: Rubber glove phantom used for verifying VU: Standard surface volume rendering vs. VDP with opacity modulation (Note the mass in the thumb that can be seen)

4.2.1 Translucent surfaces

One approach to display far surfaces through the near surface would be to set the transfer function to render each surface partially transparent. However, several studies¹⁵ have shown that untextured translucency is a poor method for conveying shape, as the human visual system is not adept at interpreting the shape of such surfaces (Figure 10). Even improved textured techniques^{15, 28} are not suitable for VA because the near surface is of no interest, and even screen-door transparency occludes portions of the far surface and renders portions of the far surface transparent, possibly hiding pathology.

4.2.2 Clipping plane

An earlier attempt at viewing the surface of interest through occluding surfaces was to use a clipping plane to cull the occluding surfaces. This technique had two limitations. The first was that the position of a user-defined clipping plane must be constantly updated by the user when moving to new viewpoints. Although this drawback can be alleviated by placing a fixed clipping plane in the space between the two surfaces, for structures like ball-and-socket joints no single clipping plane is sufficient to render the entire far surface (Figure 14). In the case of complex joint surfaces, defining a more complicated clipping geometry is equivalent to performing a manual segmentation of the joint space, a very tedious process that must be performed for each data set. In essence, VDP can be viewed as a technique for automatically defining an optimal data-dependent clipping surface.

4.2.3 Pre-segmentation

Another possible technique for viewing the surface of interest is performing a manual or automatic pre-segmentation of the surfaces, and manually selecting which surface to display. In many cases, this approach is valid, although segmentation techniques are often slow, with various parameters to fine-tune. VDP is designed for rapid ease of use by physicians, and requires no explicit segmentation. In addition, there are various configurations in which straight-forward rendering of segmented data will not work. For any non-convex surface, there are views from which even a segmented surface will occlude itself (Figure 15). Such irregular surfaces occur in locations such as bone fractures and folded surfaces (Figure 13). Similarly, no segmentation is able to render the interior surfaces of objects from outside the object (Figure 16), although isosurface generation and depth peeling techniques can work in some situations. These views of interior surfaces were the views sought by physician colleagues for performing VU. VDP handles these

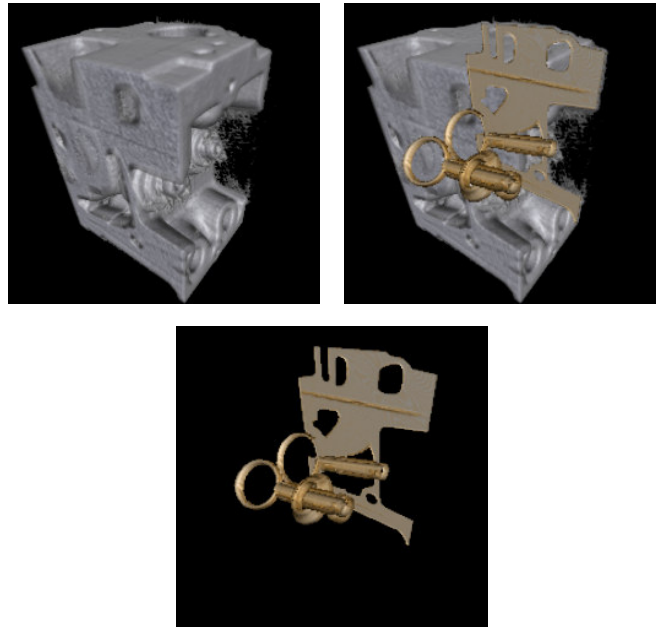


Figure 12: Engine: Standard volume rendering with some transparency vs. VDP displaying non-culled rays to give context vs. VDP removing non-culled rays to remove distraction

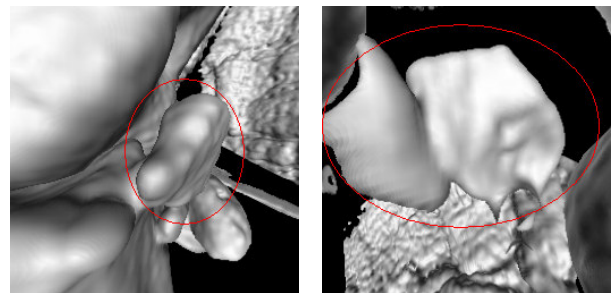


Figure 13: CT of Elbow Fracture: Restricted view vs. view of fracture from inside the bone the fracture broke from

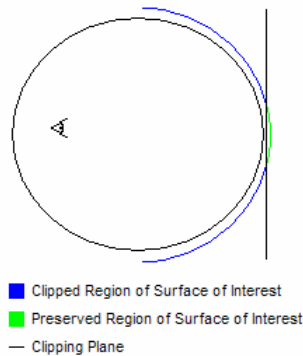


Figure 14: Clipping plane diagram

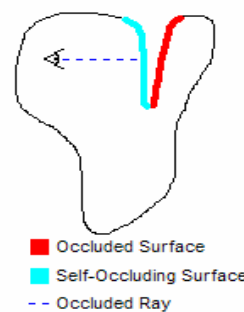


Figure 15: Self-occluding surface

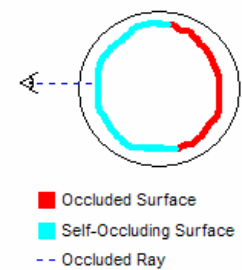


Figure 16: Interior surface occlusion

configurations with no special cases (Figure 6).

4.2.4 Isosurface generation

Another possible technique for viewing the surface of interest through occluding surfaces is defining an isosurface at the correct isovalue to represent the surface of interest, and rendering the resulting geometry with back-face culling turned on. This technique works under certain conditions, but there are common configurations in which it is insufficient. Figure 17 shows a configuration where back-face culling enables viewing the far surface because all the normals of the occluding surface face away from the viewpoint. However, in Figure 18, we see the configuration that generally arises. In this case, simple back-face culling does not remove the entire near surface, as there are front-facing polygons of the occluding surface between the viewpoint and the surface of interest. Using depth peeling techniques can remedy this problem. However, this technique will require the user to enable and disable depth peeling when maneuvering into and out of the joint space, whereas VDP enables seamless maneuvering without any further user interaction.

Additionally, generating a good isosurface of cartilage surfaces in MRI images is problematic due to inhomogeneities in the data, VDP enables more sophisticated transfer function design and the full range of transfer function effects. Generating and rendering isosurfaces with depth peeling can be viewed as an approximation to a subset of the full functionality of VDP that might be useful in certain situations.

4.2.5 View extracted joint space

Another possible technique for viewing the surface of interest through occluding surfaces is to extract the joint space (the area filled with contrast agent) either with an isosurface, or with another segmentation method, and view the resulting geometry with front-face culling turned on. Defining an isosurface of the joint space has the same problems as described in Section 4.2.4, and even an accurate segmentation of the joint space will have the same problems as described in Section 4.2.3. However, a pre-segmented joint space could be used to determine occlusion within the VDP algorithm.

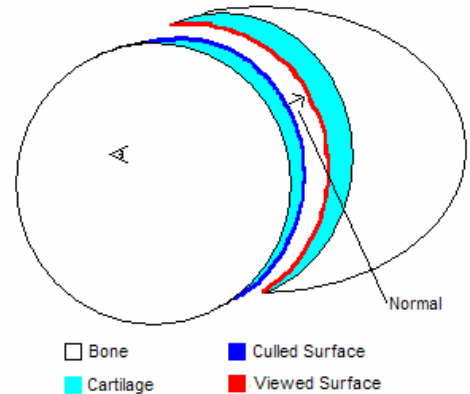


Figure 17: Back face culling works

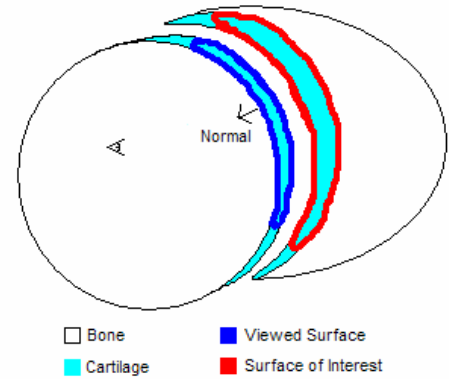


Figure 18: Back face culling does not work

5. RESULTS

The VDP algorithm has been incorporated into an application for viewing MRI and CT data built on top of the Visualization Toolkit (VTK) and the Fast and Light Toolkit (FLTK). A phantom validation study of using VDP for VU is currently underway, and a clinical validation using real data is planned. Forthcoming publications will present results of these studies. A full local Investigational Review Board approved evaluation study is also currently underway for VA of shoulder joints, and a forthcoming publication will provide full details. Viewing several shoulder data sets with this application has enabled collaborators to instantly recognize pathologies within the joint, even prompting one surgeon to state that he would change how he approached the surgery based on VDP-generated images versus viewing MRI slices due to his greater appreciation of the size and shape of a particular lesion. Some preliminary results are discussed here.

The shoulder is a ball and socket joint consisting of the humeral head (the ball), and the glenoid (the socket). The glenoid is a relatively shallow socket, so various ligaments and tendons are necessary to keep the humeral head in place. These ligaments and tendons are apt to be injured. In Figure 19, an overview of the glenoid is shown. This view is created by placing the virtual camera inside the humeral head, using VDP to remove the occluding volume of the humeral head. A view such as this is useful to the physician for performing an initial survey of the glenoid to check for

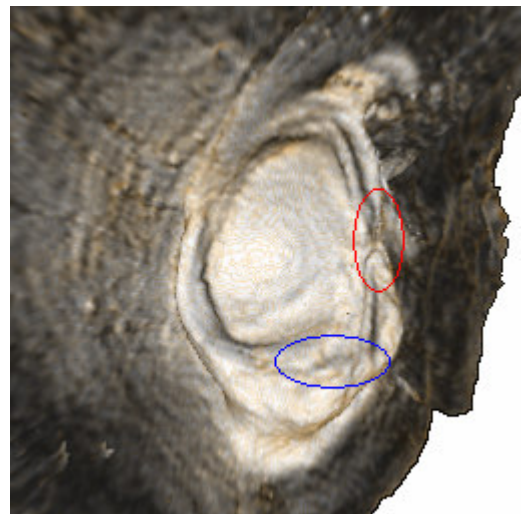


Figure 19: Glenoid survey view displaying torn ligament (red) and Bankart lesion (blue)

Standard volume rendering

Volumetric depth peeling



Figure 20: Comparison of ligament tear views

pathology, and is not possible using standard volume rendering. In this case, the physician was able to immediately diagnose the torn middle glenohumeral ligament, circled in red, and the Bankart lesion, circled in blue.

Figure 20 shows closer views of the torn ligament. On the left is a view created using standard volume rendering from within the joint space. The curved surface to the left is the humeral head, which is nearly touching the glenoid. The torn ligament is circled in red. Because the virtual camera is constrained to the joint space, the tear must be viewed at an angle and very close to the tear, making it difficult to find and diagnose. On the right is a view created using VDP. Once again the tear is circled in red, and in this view it is much easier to see the tear and place it in context with neighboring anatomical structures.

Standard volume rendering

Volumetric depth peeling

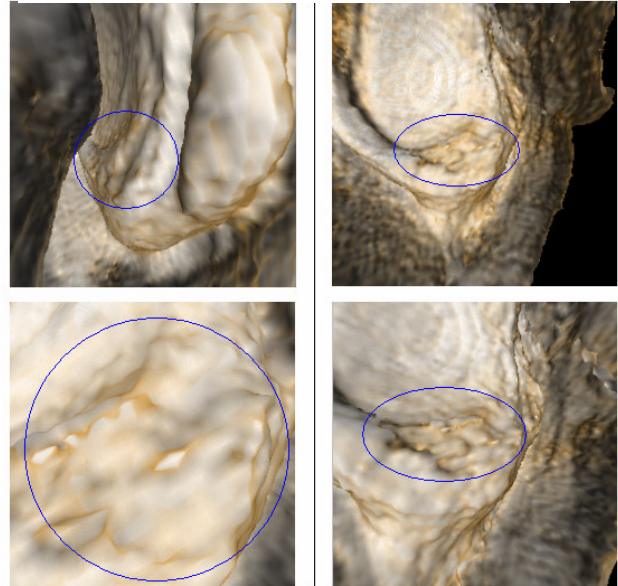


Figure 21: Comparison of Bankart lesion views

Figure 21 shows closer views of the Bankart lesion, with the lesion circled in blue. On the left are views created using standard volume rendering. As with the view of the ligament, the camera is forced to be either at an extreme angle, or extremely close to the lesion. On the right are views created with VDP, enabling unconstrained placement of the virtual camera to get better views of the lesion.

Moving into the glenoid and turning around gives an overview of the humeral head when using VDP, a view not possible with standard volume rendering (Figure 22). Inspection of the humeral head from a different position reveals a Hill Sachs lesion. Figure 23 shows views of this Hill Sachs lesion, circled in red. On the left is a view created using standard volume rendering. Once again, the viewpoint is constrained to a position very close to the lesion. On the right is a view created using VDP, more effectively demonstrating that the lesion cuts across the entire face of the humeral head, a fact not appreciated with either MRI slice viewing or standard VA.



Figure 22: Humeral head survey view

Standard volume rendering

Volumetric depth peeling



Figure 23: Comparison of Hill Sachs lesion views

6. SUMMARY AND CONCLUSIONS

VDP is a technique for automatically displaying otherwise occluded features of interest in volume data sets. VDP is a simple addition to current volume rendering systems that requires no pre-segmentation and solves visibility problems due to single, multiple, and self-occlusion. VDP is independent of transfer function definition, leaving available the full range of transfer function effects. Additional effects can be generated by discarding or modulating accumulated color and opacity and discarding or displaying non-culled rays. VDP was developed for medical applications, but has been demonstrated on other volume data sets.

VDP has been used for displaying various data sets, including MRI images of various joints, and CT images of the urinary system. VDP of MRI images of shoulders met its design goal of enabling collaborating physicians to rapidly determine pathology within the shoulder and has been extended to enable rapid survey of bone fracture and kidney collection systems.

A video demonstrating VDP on a shoulder MRI dataset is located at <http://www.cs.unc.edu/~borland/VDP/VDP.mpg>

7. FUTURE WORK

The major limitation of the prototype implementation of VDP is that a fixed threshold does not always produce a complete surface in areas where the two surfaces are touching or close to touching. Due to partial-volume effects (averaging over voxels during the MRI acquisition), it is possible that even in areas where there is no physical contact between the two surfaces, the resolution of the MRI scan may not be sufficient to define a threshold as high as in other areas of the volume. In this case, artifacts resembling holes in the surface appear. Such configurations are also problematic for isosurface and pre-segmentation techniques. We are investigating the use of more sophisticated opacity functions, involving both gradients and intensities, to address this case. This approach is the equivalent of using multi-dimensional transfer functions for opacity.

Currently, VDP uses a software volume renderer. It would be interesting to adapt the algorithm to run on GPUs. Currently, a single WEDESS MRI sequence is used for determining the appearance and visibility of the shoulder joint data. It may prove useful to incorporate other sequences to aid in determining volume boundaries. Full studies of MRI data of other joints, such as hips, wrists, ankles, and elbows are also planned, as are studies of CT urograms and bone fractures. VDP may also prove useful for other virtual -oscopy techniques, such as bronchoscopy and colonoscopy, as well as any discipline that uses volume rendering to view data where occlusion is a problem, such as geological surveying.

8. ACKNOWLEDGMENTS

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