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ORIGINAL ARTICLE

Shape-enhanced maximum intensity projection

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Abstract Maximum intensity projection (MIP) displays the voxel with the maximum intensity along the viewing ray, and this offers simplicity in usage, as it does not require a complex transfer function, the specification of which is a highly challenging and time-consuming process in direct volume rendering (DVR). However, MIP also has its inherent limitation, the loss of spatial context and shape information. This paper proposes a novel technique, shape-enhanced maximum intensity projection (SEMIP), to resolve this limitation. Inspired by lighting in DVR to emphasize surface structures, SEMIP searches a valid gradient for the maximum intensity of each viewing ray, and applies gradient-based shading to improve shape and depth perception of structures. As SEMIP may result in the pixel values over the maximum intensity of the display device, a tone reduction technique is introduced to compress the intensity range of the rendered image while preserving the original local contrast. In addition, depth-based color cues are employed to enhance the visual perception of internal structures, and a focus and context interaction is used to highlight structures of interest. We demonstrate the effectiveness of the proposed SEMIP with several volume data sets, especially from the medical field.

Keywords Maximum intensity projection · Phong shading · Tone reduction · Depth-based color · Shape perception

1 Introduction

Direct volume rendering (DVR) is a well-established visualization method for the interactive exploration of volumetric data in a variety of fields, e.g. medicine and geophysics. The usability of DVR largely depends on the transfer function, which defines a mapping from data properties to optical properties. Although a large number of classification techniques have been proposed for the automatic/semi-automatic specification of transfer functions, it is still a tedious and highly challenging task to highlight features of interest and dampen others as the context, even for skilled researchers [12]. Maximum intensity projection (MIP) [26], a variant of direct volume rendering, uses the maximum intensity along the viewing ray to determine the color of the corresponding pixel. Compared to DVR, MIP can generate a feasible visualization result without specifying a well-designed transfer function. Thus, MIP is widely used in the medical area due to its simplicity usage, such as the extraction of vascular structures in the angiography imaging [22]. However, MIP results do not provide sufficient spatial context information, and this leads to the difficulty of depth and shape perception of features.

This limitation has gained much attention in the visualization community, and several novel techniques have

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been proposed to improve the spatial comprehension of features in MIP. Heidrich et al. [11] introduced a depth-based modulation for the data value to enhance depth perception, i.e., the maximum value far away from the viewpoint is displayed much darker than the same value near the viewpoint. Depth-enhanced maximum intensity projection (DEMIP) [6] uses occlusion revealing and depth-based coloring to disambiguate the ordering of internal structures. These depth-based intensity modulations provide the spatial context, but also make structures far away from the viewpoint hard to distinguish due to the lack of contrast. Local maximum intensity projection (LMIP) [23] displays the first local maximum above the user-defined threshold, and it provides spatial continuity for better understanding of complex structures. Maximum intensity difference accumulation (MIDA) [3] adaptively adjusts the accumulated opacity and intensity to integrate the advantages of DVR and MIP. All these approaches enhance the spatial comprehension of internal structures, especially depth perception. However, local shapes and fine details of features are still little depicted.

In DVR, gradient-based shading is commonly used to reveal the appearance of surface structures. As the maximum intensity of each viewing ray is located in more or less homogeneous regions, the gradient is easily ruined by the noise caused by relatively weak differences in data values. The gradient at the position of the maximum intensity is not valid for shading in MIP and would result in disturbing illumination effects. To avoid invalid shading effects, MIDA [3] applies a blending between the unshaded color and the shaded color based on the gradient magnitude, but this would result in structures much darker than the normal lighting and produce limited lighting effects. It is much challenging to combine MIP with lighting to better enhance shape and detail perception of features.

This paper proposes a novel shape-enhanced maximum intensity projection (SEMIP) technique, which employs gradient-based shading to provide shape cues and detail information about internal structures in MIP. The core of SEMIP is to find a valid gradient for the maximum intensity of each viewing ray. The valid gradient should be able to depict the shape and detail of structural surface, and also able to represent the gradient of the feature containing the maximum intensity. This can be achieved by searching the boundary of the feature along the viewing ray before the position of the maximum intensity. The found gradient in the boundary is regarded as a valid gradient for the maximum intensity, and the Phong local illumination model [17] is then applied to enhance shape perception.

Since MIP already renders each pixel using the maximum intensity along the viewing ray and these maximum intensities may reach the maximum intensity of the display device, illumination effects would not enhance the local contrast of features in the bright area, such as the bone and vascular. Actually, this problem has been well investigated as tone reduction [5] in the computer graphics community. Tone reduction is a technique to map high dynamic range (HDR) images to low dynamic range (LDR) images, such as the range 0–255, and it has been used in volume visualization for the HDR volumetric data [28]. Thus, we resort to tone reduction to solve the lighting problem in SEMIP to preserve the local contrast of structures.

In addition, depth-based color cues are added to further improve depth perception, and a focus and context interaction is provided to selectively highlight features of interest with lighting, while preserving other features with the original MIP colors as the context. Figure 1 shows the rendered results of different visualization techniques. It is clearly seen that SEMIP provides abundant depth, shape, and detail information compared to MIP and DEMIP, such as the boundary of the shoulder, the shape of the colon, and the detail on the vertebra.

The paper is structured as follows. The related work is discussed in Sect. 2. Section 3 details SEMIP, including the valid gradient search, MIP lighting, and tone reduction. In

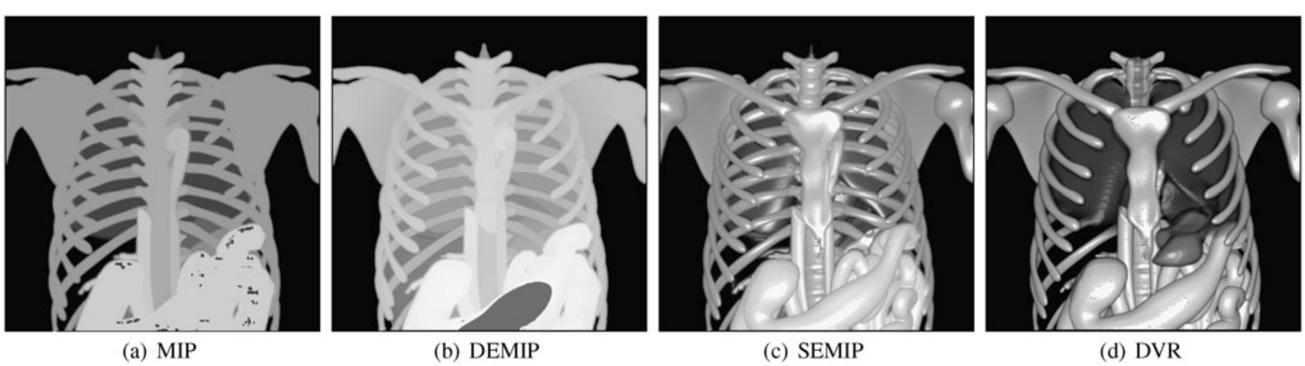


Fig. 1 The rendered results of MIP, DEMIP, SEMIP, and DVR for the ncat_phantom volumetrical data ($256 \times 256 \times 256$). (**a**) The traditional MIP result. (**b**) The DEMIP result. (**c**) The SEMIP result, which provides more shape cues and detail information than the results of MIP and DEMIP. (**d**) The DVR result

Sect. 4, we describe depth-based color cues and a focus plus context interaction. We show and discuss several results of SEMIP in Sect. 5. Finally, we give concluding remarks in Sect. 6.

2 Related work

The transfer function plays a crucial role in DVR, and it receives continuous attention from researchers in the visualization community. Various derived properties have been proposed, such as the second directional derivative along the gradient direction [14], the curvature [13], and the shape size [4], and these properties introduce additional new dimensions to better separate features of interest, but the specification of an appropriate transfer function is still very complex and time-consuming.

A realistic illumination model could effectively enhance perception of features in a natural way. In DVR, the most common physically-based optical model is absorption plus emission [17], i.e., each voxel emits light and absorbs incoming light. The Phong local illumination model is one of the widely used illumination models, and shadow effects are incorporated into DVR by Behrens and Ratering [1]. Kniss et al. [15] presented a volume lighting model and showed various effects, such as volumetric shadows and forward scattering. A thorough overview of advanced illumination techniques for GPU volume ray-casting can be found in [21]. In this paper, we apply gradient-based lighting in MIP to provide the spatial context expressively.

Illustrative techniques are usually used to improve the perception of depth and structure in DVR. Ebert and Rheingans [9] introduced various feature and orientation enhancements, such as boundary enhancement, silhouette enhancement, tone shading, distance color blending, and distance color cues. Nagy et al. [20] added line rendering to DVR, as feature lines are one of the most effective visual abstractions for highlighting features of interest in traditional illustrations. Bruckner and Gröller [2] proposed volumetric halos to enhance depth perception, while Svakhine et al. [25] discussed illustration-inspired effective outlining techniques and selective depth enhancement.

MIP was first proposed by Wallis et al. [26] for the exploration of Positron Emission Tomography (PET) data, and a low-complexity algorithm based on the octree has been proposed for interactive MIP rendering of large volumes [18]. As MIP highlights high-intensity data values, it can produce a feasible visualization result without the specification of complex transfer functions. Due to the missing spatial context and shape information in MIP, many efforts have been made to resolve this limitation. The common way resorts to viewing the volume from different viewpoints by rotation to reconstruct the spatial context by the user [19]. Heidrich et al. [11] proposed a depth-based modulation for the data value along the viewing ray to improve depth perception. Sato et al. [23] suggested to display the first local maximum rather than the global maximum to provide more clear spatial context. MIP and DVR were first fused in two-level volume rendering [10] for a single volumetric data based on the pre-classification, and Straka et al. [24] applied a combination of rendering techniques for vascular structures. MIDA presented by Bruckner and Gröller [3] can be used for the smooth transition between DVR and MIP. Like MIP, MIDA does not require complex transfer functions, but has the spatial and occlusion context like DVR. Although MIDA combines gradient-based shading to enhance shape perception, the gradient at the position of the maximum value is inaccurate for shading. Our proposed approach searches a relative valid gradient to represent structural surfaces of the maximum intensity, and integrates gradient-based shading of DVR into MIP.

Ropinski et al. [22] emphasized depth cues by changing the color of the maximum intensity based on its position (pseudo chromadepth). This color cue allows the user for better judgement of the spatial context. DEMIP proposed recently by Díaz and Vázquez [6] searches the similar material before the maximum intensity, and utilizes the depth of the similar material to adjust the color in order to enhance depth perception. Like pseudo chromadepth, DEMIP also uses the color sphere to further distinguish the spatial order of internal structures. Our gradient search method is inspired by the search of DEMIP's similar material. In addition, our gradient-based lighting is orthogonal to the depth-based color modulation. We can use both techniques to enhance shape and depth perception in MIP.

3 Shape-enhanced maximum intensity projection

MIP depicts internal structures inside the volume without a complex interaction, and it is especially useful in the field of medicine. The proposed shape-enhanced maximum intensity projection (SEMIP) further provides the spatial context and shape information for users, which could enhance shape and depth perception of internal structures for the detailed exploration. Figure 2 illustrates the pipeline of the proposed SEMIP. The original MIP is firstly performed to obtain the value and position of the maximum intensity of each viewing ray. Ray-casting is then used to search a valid gradient before the position of the maximum intensity along the viewing ray, and this should be located at the boundary of feature containing the maximum intensity. The found valid gradient is referred to as the representative gradient in the rest of this paper. Based on the representative gradients, the Phong local illumination model is applied to produce shading effects for structural surface, and then a tone reduction technique is introduced to compress the intensity range

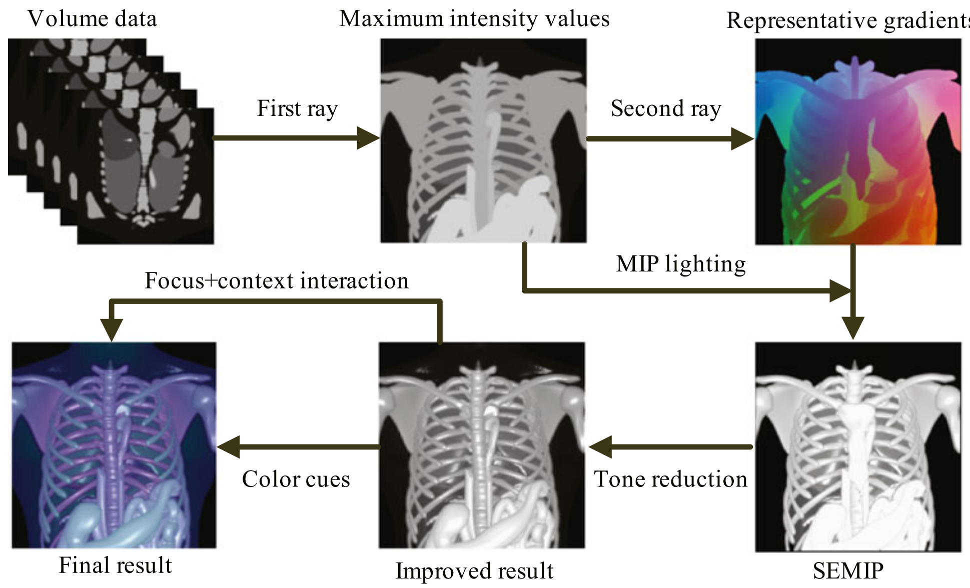


Fig. 2 The SEMIP pipeline. A two-pass ray-casting operation is used to search the representative gradient of the maximum intensity. The Phong shading is then performed to enhance shape perception of internal structures. Moreover, tone reduction is applied to optimize the rendered result. At last, two visual enhancement techniques can be used to improve the visual perception of structures

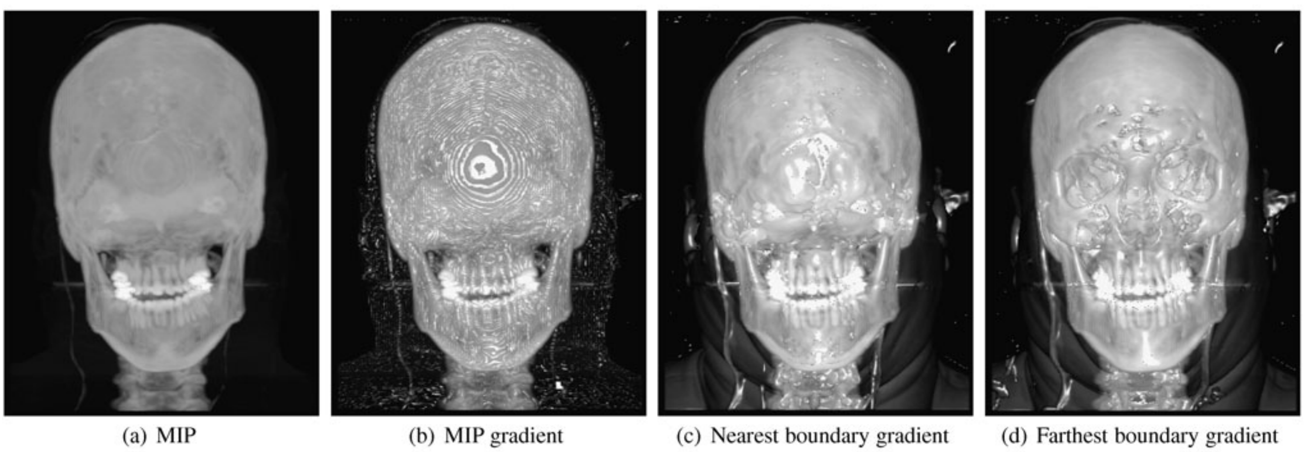


Fig. 3 The comparison of gradient-based shading based on different found gradients. (**a**) The MIP result. (**b**) The rendered result based on the gradient of the maximum intensity. (**c**) The rendered result based on the gradient of the nearest boundary from the maximum intensity. (**d**) The rendered result based on the gradient of the farthest boundary from the maximum intensity. The same global threshold is used for the valid gradient search in (**c**) and (**d**)

while preserving the local contrast of the rendered image. In addition, depth-based color cues are used to further improve depth perception of internal structures, and the user can use a focus and context interaction to emphasize structures of interest using the SEMIP colors. The details of these steps are discussed in the following subsections.

3.1 Representative gradient search

DVR employs gradient-based shading to improve the visual perception of features. In order to apply such shading in MIP, it is necessary to obtain a valid gradient for the maximum intensity. One simple choice is the gradient at the position of the maximum intensity. However, it has been proved that such gradient is inaccurate and produces poor lighting effects for visual perception, as shown in Fig. 3(b). This is because the maximum intensity may be located in the homogeneous area, and the gradient at that position tends to zero or deviates from the correct orientation of the structural surface due to relatively weak differences in data values.

As the valid gradient should be able to depict the orientation of the structural surface, it must be located in the boundary of feature. The valid gradient is selected from the gradients before the position of the maximum intensity along the ray, and it should be near the maximum intensity. Thus, the valid gradient can be obtained by casting a ray back from the position of the maximum intensity to the viewing plane to search the first valid gradient in the boundary. Although this gradient is more accurate than the one at the position of the maximum intensity, the lighting effects may be not con-

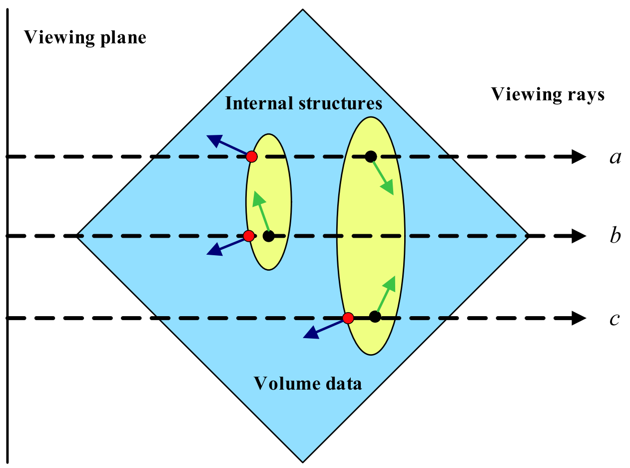


Fig. 4 The representative gradient search in different viewing rays. Yellow areas present the internal structures. The black point indicates the positions of the maximum intensity of each viewing ray, while the red one is the position on the structure's boundary in the second ray casting. Green arrows are the gradient directions of the maximum intensities, and blue arrows present the gradients of the boundaries, which are the representative gradients

tinuous on the rendered image, as shown in Fig. 3(c). This can be explained by the fact that the positions of the maximum intensity among neighboring rays may present little coherence due to the independent ray casting, and they may be in different structures of the same feature.

Figure 4 illustrates the relationship of the maximum intensity and its valid gradients. If the structure of the maximum intensity is not occluded by other structures of the same feature (such as the bone) from the viewing direction, there is only one valid gradient discussed above (the viewing rays b and c in Fig. 4). Otherwise, there would be several valid gradients available among all gradients before the position of the maximum intensity, and they are all located at the boundaries of different structures of the same feature (the viewing ray a in Fig. 4). We can take the farthest valid gradient, not the nearest valid gradient, from the position of the maximum intensity as the representative gradient of the maximum intensity. In this way, the representative gradients are all located in the boundaries of the nearest structures from the viewing direction, and these continuous gradients would present coherent lighting effects, as shown in Fig. 3(d).

The method to find the nearest structure from the viewing plane is inspired by the one to locate the similar material in DEMIP [6]. In order to obtain the representative gradient, a ray is cast from the viewing plane, and terminated at the nearest structure of the same feature to which the maximum intensity belongs. The intensity value of the nearest structure is similar to the maximum intensity, and we use a global threshold to check whether the value is in the intensity range of the feature. The user can adjust the similarity of two structures by changing the global threshold. Due to the difference between the value at the terminated position and the maximum intensity, the terminated position would be usually in or near the boundary of the structure, and the gradient at that position would well depict the orientation of the structural surface. The pseudo code for the search of representative gradient is shown as follows.

```
REPRESENTATIVE GRADIENT SEARCH
maxValue ← 0 // the maximum value
p ← 0 // the maximum intensity position
q ← 0 // the boundary position
// the first ray-casting (MIP).
for i ← 0 to steps
while Sample[i] > maxValue
    do maxValue ← Sample[i]
       p ← i
// the second ray-casting (search the nearest structure)
for j ← 0 to p
// threshold is used to determine the similarity
while Sample[j] > threshold * maxValue
// record the boundary position
    do q ← j
```

3.2 MIP lighting

With the representative gradients of the maximum intensity, the Phong local illumination model can be applied to enhance shape perception of structural surfaces. Formally, the color of a shaded maximum intensity can be expressed as

$$C = \big(k_a + k_d(N_{\text{valid}} \cdot L)\big) \cdot C_{\text{MIP}} + k_s(N_{\text{valid}} \cdot H)^n, \qquad (1)$$

where k_a, k_d, and k_s are the ambient, diffuse, and specular lighting coefficients respectively, n is the shininess exponent, C_{MIP} is the color of the maximum intensity, N_{valid} is the representative gradient of the maximum intensity, L is the light direction, and H is the normalized half-way direction. The shaded maximum intensity not only preserves the original maximum intensity value for the abnormal detection, but also makes the shape and boundary of structure more easily comprehensible in the rendered image. For example, Fig. 3(d) clearly presents the convex shape and smoothness of the skull.

The proposed MIP lighting is complement to other MIP enhancement techniques. For instance, C_{MIP} can be replaced with C_{DEMIP} [6], which is obtained by blending the maximum color and the depth of the similar material. This combination further enhances depth perception of the shaded result.

3.3 Tone reduction

Based on the proposed MIP lighting, lighting effects are imposed on the maximum intensity of every viewing ray. However, it is difficult to distinguish internal structures in the

Fig. 5 Tone reduction for SEMIP. The left image presents the SEMIP colors without tone reduction. Tone reduction is applied with the parameter $\eta = 0.6$ and the result is shown in the middle image. On the right, $\eta = 0.9$

bright area, because the shaded value may exceed the maximum intensity of the display device and this results in the reduction of the rendered image's contrast. This problem has been well investigated as tone reduction in computer graphics. Many tone-reduction operators have been developed to effectively map HDR images to LDR display devices while preserving the contrast of HDR images [16]. These operators can be classified into global spatially uniform operators [7] and local spatially varying operators [8]. Yuan et al. [27, 28] introduced the HDR technique into volume visualization, and presented an interactive HDR volume visualization framework. In this paper, we simply choose a global operator, the adaptive logarithmic reduction operator [7], to compress the MIP shaded result, as it is very fast and can work interactively for SEMIP. The formula of this operator is

$$C_{\text{new}} = (D_{\max} - D_{\min}) * \frac{\log(C + \gamma) - \log(C_{\min} + \gamma)}{\log(C_{\max} + \gamma) - \log(C_{\min} + \gamma)} + D_{\min}, \qquad (2)$$

where C_{new} is the resultant color values using tone reduction, $C_{\min}$ and $C_{\max}$ are the minimum and maximum color values obtained by the MIP lighting, $D_{\min}$ and $D_{\max}$ are the minimum and maximum luminance of the normal display device. $\gamma = \eta * (C_{\max} - C_{\min})$, where η is an effective parameter for users to tune the brightness of rendered images. Figure 5 shows the effectiveness of tone reduction in the SEMIP result. Without tone reduction, the shape and boundary of the colon are hard to distinguish on the left of Fig. 5. By tuning the parameter η, tone reduction reduces the intensity of the rendered images and enhances the local contrast of internal structures, especially the colon, as shown in the middle and right of Fig. 5.

4 Visual enhancements

With lighting effects, the local shape and relation of internal structures are well presented for the spatial comprehension of features. Two visual enhancement schemes are presented in this section to further enhance the visual perception of features. One is the depth-based color cues generated by the HSV color model. The other is a focus and context interaction to highlight features of interest.

4.1 Color cues

Although lighting effects improve the visual perception of structures, it is still a little difficult to distinguish the ordering of complex structures. The depth information is usually represented by the color, i.e., different colors correspond to different depths. In this paper, we resort to the HSV color model for producing depth-based color cues, to further enhance depth perception of internal structures.

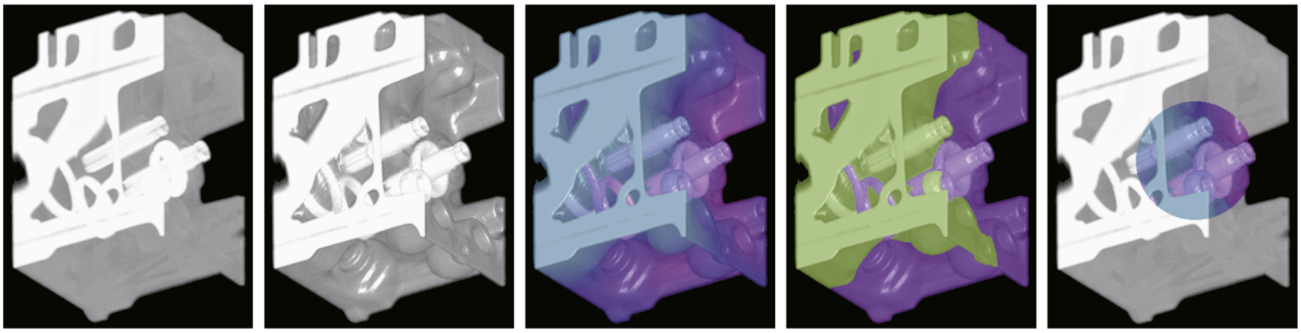
Figure 6 shows the rendered results using depth-based color cues for the engine data set (256 × 256 × 256). The MIP result in Fig. 6(a) could not identify the depth order of internal features. Although the SEMIP result in Fig. 6(b) enhances shape perception of features, the depth order of internal features is still hard to distinguish for users. Two depth-based color cues, the HSV color model and color sphere [6], are used to improve depth perception in parts (c) and (d) of Fig. 6, respectively. As a result, users can easily distinguish the depth order of internal features by the color.

4.2 Focus and context

A simple focus and context interaction is provided to highlight features of interest. The user clicks the interested feature in the MIP rendered image. The clicked position is taken as the center of ROI (region of interest) to determine a focus area, and the radius of the focus area can be further adjusted according to the user's requirement. The focus area is emphasized by the MIP lighting or depth-based color cues, while others are displayed using the original MIP color as the context. A focus and context example for the engine data set is shown in Fig. 6(e), where internal features are highlighted by depth-based color cues.

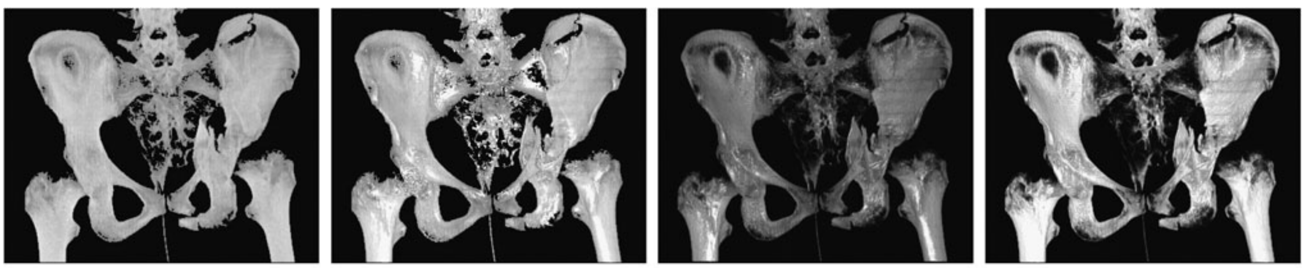
5 Results and discussion

We have implemented the proposed SEMIP in a GPU-based ray casting volume renderer using the fragment shaders in



(a) MIP (b) SEMIP (c) HSV cues (d) Color sphere cues (e) Focus and context

Fig. 6 Visual enhancements based on SEMIP for the volumetric engine data. (**a**) MIP. (**b**) SEMIP. (**c**) Depth-based color cues based on the HSV color model. (**d**) Depth-based coloring operation based on the color sphere. (**e**) The focus and context interaction



(a) MIP (b) SEMIP (c) MIDA (d) DVR

Fig. 7 The rendered results using (**a**) MIP, (**b**) SEMIP, (**c**) MIDA and (**d**) DVR for the PELVIX CT data set. MIDA and DVR use the same transfer function

the Cg shading language. All the experiments were performed on an Intel Core 2 Quad CPU Q9550 @ 2.83 GHz with 4.00GB of RAM. The graphics card is a NVIDIA GeForce GTX 260 GPU with 1.00GB of RAM. MIP, DEMIP, MIDA, DVR and our SEMIP are applied to a number of different volume data sets for the visual comparison in the information communication of internal structures.

Figure 1 shows the rendered results of the ncat_phantom data set using MIP, DEMIP, SEMIP, and DVR. Compared to MIP and DEMIP, more shape, detail, and depth information are provided in the SEMIP result. Figure 7 shows the rendered results of MIP, SEMIP, MIDA and DVR for a PELVIX data set ($512 \times 512 \times 355$). Although MIDA also supports lighting, the MIDA result in Fig. 7(c) is much darker than the SEMIP and DVR results due to the blending between the shaded color and MIP color. Like MIP, SEMIP considers the maximum intensity along each viewing ray as structures of interest. Abundant local shape cues are further presented in the SEMIP result by means of gradient-based shading, which is similar to DVR. As SEMIP have advantages of both MIP and DVR, the users could analyze shape-enhanced features in the SEMIP result more efficiently. As can be seen from Fig. 7(b), more perceptible structural shape information is well presented and the visual perception of features is largely enhanced. In addition, SEMIP does not need to specify a well-designed transfer function, and is more suitable for medical applications than DVR and MIDA.

Figure 8 shows various rendered results of an aneurism data set ($256 \times 256 \times 256$) to compare MIP, DEMIP, MIDA, SEMIP, and DVR. Figure 8(a) is the rendered result of MIP, similar to the X-ray image. DEMIP is designed to improve depth perception of feature by blending the MIP color and the depth value of the similar material, but the shape information of the aneurism is not well displayed, as can be seen from Fig. 8(b). The spatial context of the aneurism are greatly revealed in the SEMIP result in Fig. 8(c), and depth-based color cues are added in Fig. 8(d). The rendered results of MIDA and DVR based on the same transfer function are displayed in parts (e), (f) and (g) of Fig. 8. Focus and context is a useful technique to attract the user's attention to the highlighted feature. As shown in Fig. 8(h), the local context and shape information of the aneurism is highlighted, while other blood vessels are preserved as the context.

An MRI scan FELIX volume data set ($448 \times 576 \times 120$) is used to further demonstrate the effectiveness of SEMIP. Figure 9 presents the rendered results of MIP, DEMIP, SEMIP, MIDA and DVR. The MIP result as shown in Fig. 9(a) is hard to analyze the aneurism due to the lack of the context information. The DEMIP result in Fig. 9(b) presents the depth order between the aneurism and other vessels. SEMIP combines the advantages of MIP and DVR

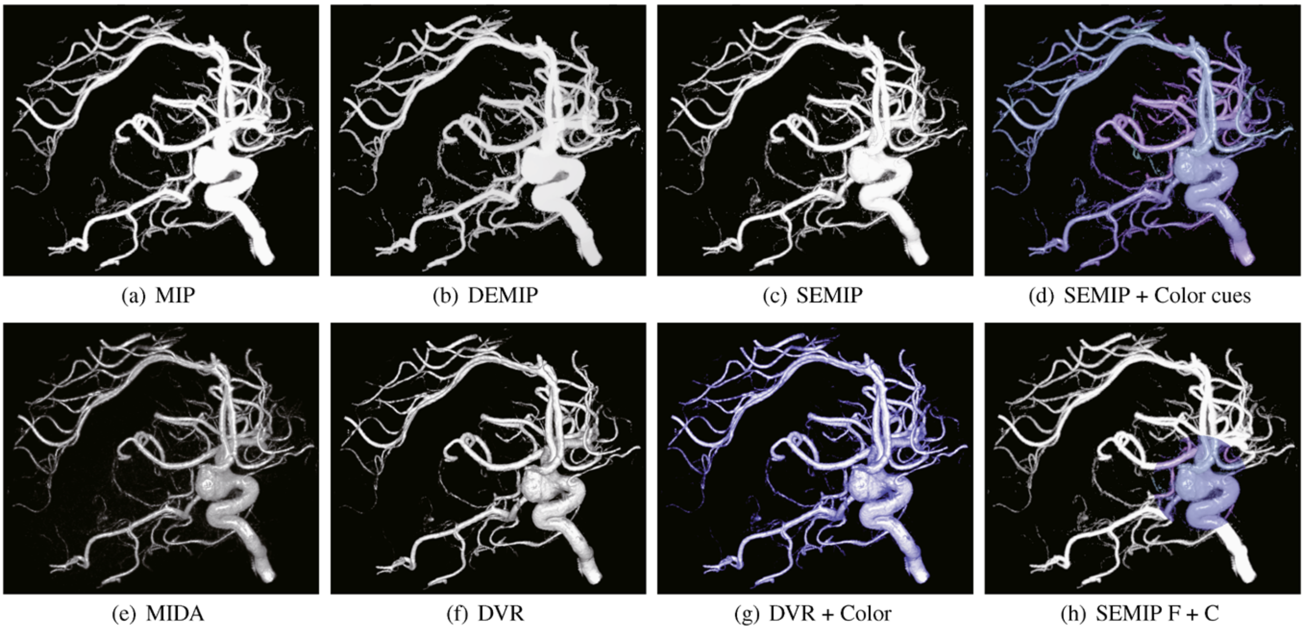


Fig. 8 The rendered results for the volumetric aneurism data set based on various rendering techniques

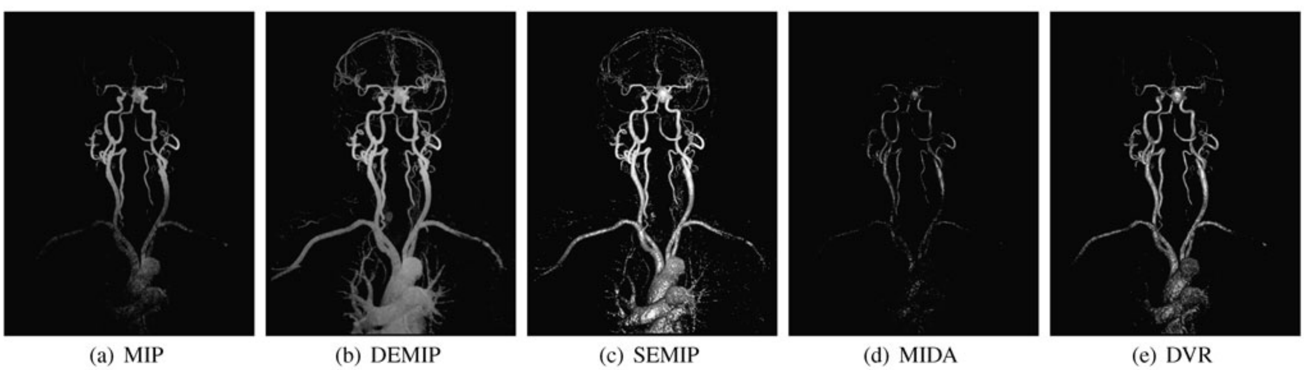


Fig. 9 The rendered results using (**a**) MIP, (**b**) DEMIP, (**c**) SEMIP, (**d**) MIDA and (**e**) DVR for the FELIX MRI data set

to provide clear shape cues of the aneurism and vessels by using gradient-based shading. Compared to MIDA and DVR, users could obtain more local shape cues and important contextual information in the SEMIP result, without the specification of a complex transfer function.

The shading effects of SEMIP largely depend on the validity of the representative gradient. A global threshold is used to determine the similarity between the current sampled value and the maximum intensity. As the maximum intensities of viewing rays are different, it is hard to set up an optimal global threshold for various situations. Currently, the users may need to try several values to find the optimal threshold for some complex data sets, and this would add more burden to the users. A local adaptive threshold would be better for the search of the representative gradient. As the representative gradient is calculated based on the sampled values of the volume, the noise in the volume would affect the accuracy of the representative gradient, similarly to the shading in DVR. Denoising methods can be used to reduce the influence of noises before applying the SEMIP rendering. Another limitation of SEMIP is the inaccurate depth order for overlapped features. As shown in Fig. 1, the lung is behind the bone. Actually, this is an inherent limitation of MIP, as MIP visualizes only the maximum intensity of each viewing ray. For overlapped features, MIP renders features according to the intensity order, and takes this order as the depth order of features. Features with the lower intensity are occluded by features with the higher intensity, even if features with the higher intensity are behind features with the lower intensity in the physical order. Fortunately, depth-based color cues can solve this problem to some extent.

Table 1 is the performance comparison between MIP, DEMIP, DVR, MIDA, and SEMIP. MIP is fastest among

Table 1 The performance comparison in fps (frames per second)

Method	Ncat_phantom	Aneurism	PELVIX	FELIX
MIP	52.6342	32.8827	15.2737	40.3712
DVR	47.6677	21.1535	15.5505	34.3322
MIDA	38.6829	20.1417	13.7135	34.7621
DEMIP	40.5504	26.7283	13.0363	35.7377
SEMIP	39.8433	20.1883	13.0834	34.7093

these rendering techniques, as it only needs to trace one ray to find the maximum value along the viewing ray. DEMIP traces two rays to look for the maximum intensity value and the similar material, while SEMIP also traces two rays to search the maximum intensity and the representative gradient. In addition, SEMIP needs to perform a costly Phong shading operation at last. Thus, the performance of SEMIP is a little worse than DEMIP. Although DVR performs Phong shading for each valid gradient, early ray termination technique makes DVR without a need to traverse the whole volume and improves the rendering efficiency compared to SEMIP for some volume data sets. However, SEMIP can fast obtain a shape-enhanced rendered result without the time-consuming specification of a well-designed transfer function.

6 Conclusion

We have presented a shape-enhanced maximum intensity projection visualization technique, which can fast render internal structures with clear shape cues and local context information. We first resort to two-pass ray casting to search the representative gradient of the maximum intensity, and then gradient-based Phong shading is applied to enhance shape perception of structures. As shaded values may be over the maximum intensity of the display device, a global tone reduction operation is used to compress the intensity range of the rendered image while preserving the original local contrast. Furthermore, depth-based color cues based on the HSV color model are utilized to improve the visual perception of structures, especially depth perception. A focus and context interaction is used to highlight structures of interest, and also improves the rendering efficiency of SEMIP. Compared to traditional rendering techniques, SEMIP presents much more shape and local detail information than DEMIP and MIP. Without a need to specify a well-designed transfer function, SEMIP is simpler and more effective than DVR and MIDA. Thus, SEMIP is more suited for medical applications.

In the future, we plan to employ a local adaptive parameter to replace the current global threshold in the representative gradient search. This will help find more accurate representative gradients for each viewing ray and provide more accurate visual perception of structures. Besides the local Phong illumination model, global illumination models such as ambient occlusion would further improve shape and detail perception. As a result, we will investigate how to integrate global illumination models into MIP.

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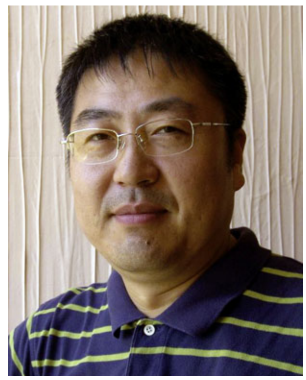

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