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胎児外科手術における三次元超音波のリアルタイム立体像表示システムの開発

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Development of Real-time Auto-stereoscopic Visualization System using 3D Ultrasound for Fetal Surgery

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Abstract: This research presents a real-time Integral Videography(IV) auto-stereoscopic visualization of 3D ultrasound for fetal surgery. We developed a fast IV rendering algorithm implemented on GPU using CUDA. To improve image quality, we developed IV composite rendering algorithm with color and alpha transfer function and Phong shading. We also developed the user interface of IV visualization system as a module of medical image processing software 3D Slicer. Implementation of IV rendering on GPU has realized real-time visualization for a frame rate of 3 fps on 256^3 dataset on 5 megapixels monitor. In phantom experiment using fetal phantom, developed algorithm showed sufficient image quality and speed. In the future, we plan to do clinical evaluation of the system.

Keywords: 3D ultrasound, Integral Videography, Fetal surgery, GPU calculation

1. 序論

いくつかの症例において，妊娠中に胎児を手術することにより生まれた後の QOL の大幅な向上に繋がる場合が多いため，胎児外科手術が有望な手術手法だと言われている．胎児が養水の中に浮いていて手術中に常に移動・変形をするため，術前画像による誘導は誤差の原因となる．そこで，術中画像を用いる手術誘導が大事である．リアルタイムで三次元画像が取れることが必要条件であり，三次元超音波を用いることが有効だと考えられる．

リアルタイムで取得したデータを手術誘導に使うには，リアルタイムな視覚化も必要になる．また，リアルタイム画像で手術を誘導するには，奥行き情報が直感的に分かりやすい立体画像で視覚化する事が有効だと考えられる．これまで Integral Videography(IV)[1]という裸眼で視覚化できる立体像表示方法を開発した．また，GPU 計算を用いることで，リアルタイムな IV 表示システムを実現した[2]．

本研究は，胎児外科手術のための三次元超音波画像のリアルタイム立体像表示による手術誘導システムの開発を行った．具体的には，高速・高画質な立体像レンダリングの開発，ユーザインターフェースの開発を行い，ファントム・in-vivo 実験にて臨床応用可能星を検証した．

2. 方法

2.1. システムの構成

本システムは，超音波診断装置(ALOKA)，処理用 PC ワークステーション(Intel Core i7 2.4 GHz，Quadro FX5800)，GPU サーバー(Tesla D870)，高解像度液晶モニタ(21.3”，2048x2560 ピクセル，モノクロ)から構成される(Fig.1)．超音波装置で取得した三次元超音波画像に対して座標変換・IV レンダリングを行い，できた IV 画像を高解像度液晶モニタに表示する．

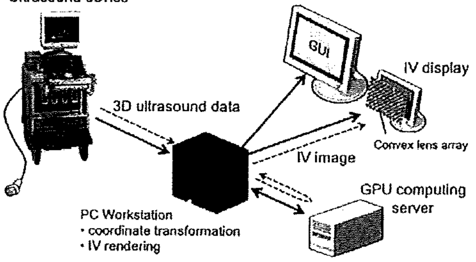

Fig.1 System configuration of real-time 3D ultrasound IV visualization system

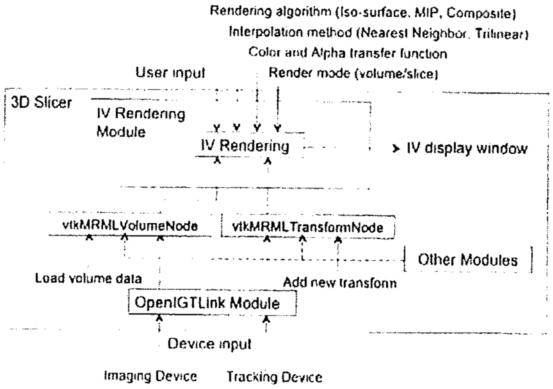

Fig.2 IV rendering module configuration

2.2. 高速IVレンダリング

リアルタイムなIVレンダリングを実現するために、IVレンダリングをGPUで実行する．IVレンダリングをCUDA[3]で実装した．

2.3. 高画質IVレンダリングアルゴリズム

IV立体像の画質を向上するために，色及び透明度のマッピングを用いたCompositeレンダリングを開発した．また，奥行き感を高めるために，Phongシェーディングを実装した．

2.4. ユーザインターフェースの開発

多機能・拡張性の良いユーザインターフェースを実現するためには，オープンソース医用画像処理ソフトウェア 3D Slicer[4]を利用し，IV立体像表示機能を拡張モジュールとして開発した．3D Slicerは様々な三次元データフォーマットの読み込み，画像レジストレーション・セグメンテーション機能などが充実した上，独自のMRMLデータ形式を使用しどの処理段階の三次元データも同様に扱うことができる．そのデータ形式の一様性を利用してIV立体像表示モジュールもMRMLデータ形式のみを考えれば済むという利点を持っている．

3. 結果

GPUを用いてリアルタイムIVレンダリングを実現した．256^3ボクセルデータを大型高解像度液晶モニタ（21.5"）に3 fps程度の画像更新速度が得られた．胎児ファントムを用いた実験・in-vivo実験では，開発したIVレンダリングアルゴリズムが十分な速度・画質を有することが分かった(Fig.3, Fig.4)．

4. 考察・結論

本研究では，リアルタイム三次元超音波画像に対するリアルタイム立体像表示システムを実現した．異なる画像コントラストの超音波画像ごとにレンダリングパラメタを調整する必要があるが，自動的に調整する手法を考えるべきである．今後，このシステムを用いて臨床評価を行う予定である．また，手術誘導を目標として，手術器具の視覚化や内視鏡画像との統合を行いたいと考えている．

Fig.3 Phantom experiment: IV visualization of 3D ultrasound image of fetus phantom

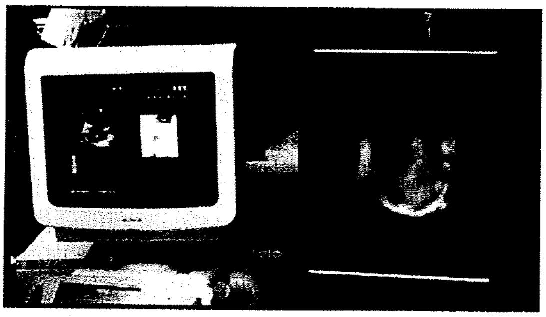

Fig.4 In-vivo experiment: IV visualization of 3D ultrasound image of porcine beating heart

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Realtime Integral Videography Auto-stereoscopic Surgery Navigation System using Intra-operative 3D Ultrasound: System Design and In-vivo Feasibility Study

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Abstract. 3D ultrasound is non-invasive and fast imaging method suitable to guide surgeries with large intra-operative organ movement and deformation. But it is usually displayed on 2D screen so depth information is difficult to percept. In this paper, we present real-time Integral Videography (IV) auto-stereoscopic surgery navigation system using intra-operative 3D ultrasound. The system visualized 3D ultrasound data as high quality auto-stereoscopic images in real-time. We improved IV image quality by adding Phong shading into original composite algorithm, implemented on GPU for real-time calculation. Comparison with original method showed that the use of Phong shading for IV improved depth perception and reality of IV images, with performance decrease of less than 50%. As clinical feasibility study, we conducted an in-vivo porcine experiment simulating mitral valve surgery on beating heart, guided with real-time auto-stereoscopic image of intra-operative 3D ultrasound. The experiment showed that our system is fast enough to follow heart beat. Surgical tool was visible clearly and succesfullly driven towards surgery target. We also received qualitative evaluation from expert cardiologist that time lag was within tolerable range.

1 Introduction

3D Ultrasound is the fastest imaging technology capable of acquiring 3D images of human body in real-time. This capability, along with the fact that ultrasound is non-invasive, has brought 3D ultrasound to be used for diagnostic and surgeries. Unfortunately, 3D images acquired are usually displayed as a 3D view on 2D screen. Displaying 3D view on 2D screen causes lack of depth perception. Surgeons may have to rotate the viewing angle of the 3D view to percept depth information. While it may be enough for diagnostics where there are plenty of time for decission, it is not practical for surgeries, especially for surgeries with

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large organ movement and deformation where decision time is minimal, such as beating heart surgery. A more intuitive vizualizion way such as stereoscopic display is required.

We have developed an auto-stereoscopic visualization method called Integral Videography(IV)[1, 2]. The principle of IV to display a stereoscopic image is by projecting lights from high-resolution LCD screen onto 3D space in front of the screen by using micro convex lens array. Compared to other stereoscopic visualization method such as binocular stereoscopic, IV has many advantages, such that it doesn't need glasses or other viewing devices, it is visible by many people at the same time, and it is spatially accurate. The fact that it is spatially accurate makes it possible to use it in applications such as IV overlay, augmenting IV stereoscopic image with patient's body.

However, in order to bring IV into operating room, there are still many issues to solve. First, IV rendering, the calculation to create an IV stereoscopic image from 3D data is heavy computationally. Second, current IV rendering algorithm lack image quality. Third, there is a need for user interface for surgery navigation purpose. Herlambang et al. have developed a fast IV rendering algorithm using GPU implementation[3], and a composite IV rendering method for high image quality rendering[4]. Implementation of IV rendering algorithms on GPU has made it possible to display IV images in real-time. And composite rendering for IV has improved image quality significantly, though lack of shading algorithms is still room for improvements.

In this paper, we developed a real-time IV surgery navigation system using 3D ultrasound. In details, we added shading algorithm into composite IV rendering algorithm, develop the user interface, and finally performed an in-vivo feasibility study.

2 Method

2.1 System Configuration

Fig 1 shows system configuration of the real-time IV visualization system. It consists of an ultrasound device(α10, ALOKA), a workstation (Quad Core 2.4 GHz, 4GB), an LCD screen for GUI display, and an IV stereoscopic display. The ultrasound probe used is 3D convex probe that can acqurire 3D image up to 10 volumes/s, in trade-off with image resolution and quality. The 3D ultrasound data is sent to workstation in real-time through LAN and LVDS connection. Acquired 3D ultrasound data is then processed on the workstation, with help of GPU computing server, and the resulted IV image is displayed on the IV display. As the IV display we used a high resolution LCD screen (6.4 inch XGA). We used convex lens array with lens diameter of 1 mm arranged in hexagonal configuration.

2.2 IV Rendering Algorithm

IV rendering algorithm to create IV image from 3D data is based on ray-tracing algorithm. The image value of each pixel on LCD screen is calculated by ray

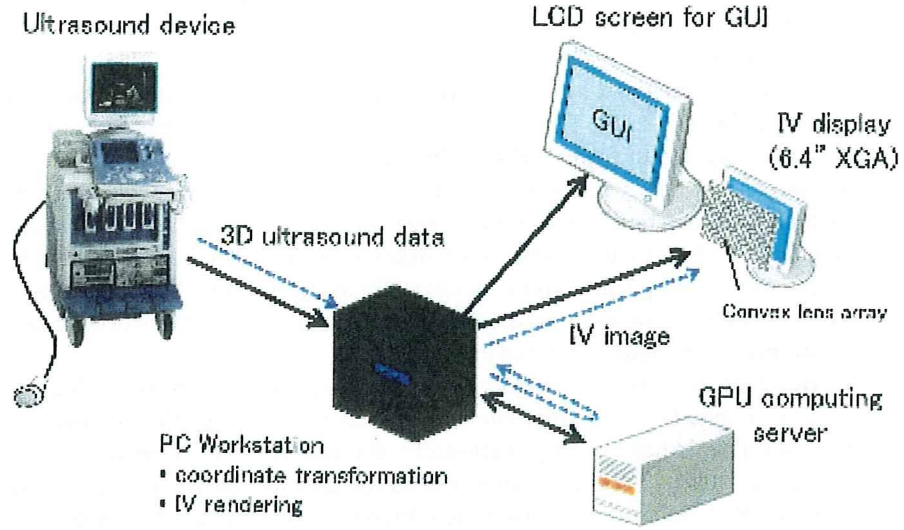


Fig. 1. System configuration.

tracing along the light ray connecting the pixel and center of corrensponding convex lens. We have developed composite rendering algorithm for IV, which use color and alpha transfer function to each voxel value, and use those values as color and transparency of each voxel when doing ray tracing. To improve previous algorithm, we implemented Phong shading algorithm[5]. Previous algorithm without shading only calculated ambient component of Phong shading, while the proposed algorithm also calculated diffuse and specular components (Fig 2). In Phong shading calculation, there is a need to also calculate gradient field of image data. Gradient field, also implemented on GPU and pre-calculated on each image update, is then used to calculate diffuse and specular components.

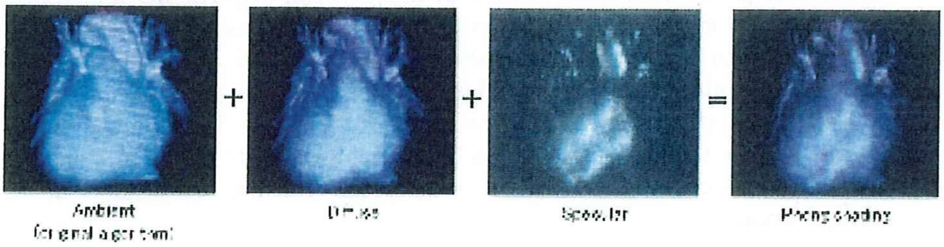
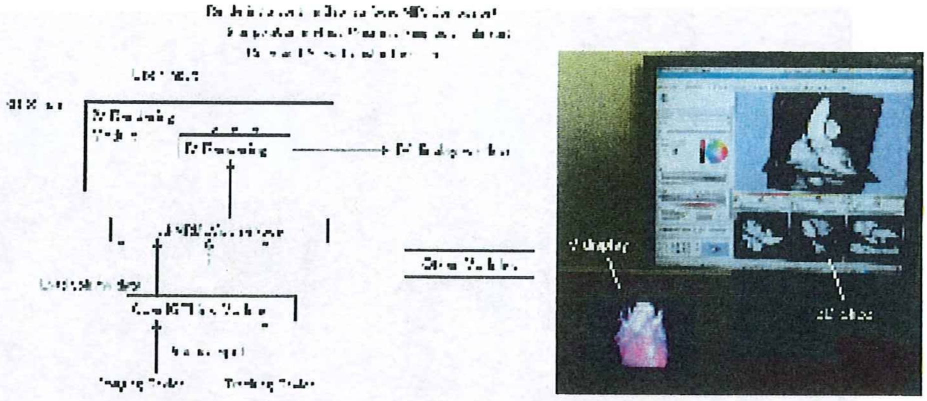


Fig. 2. Phong shading for IV stereoscopic image. In addition to ambient component of original algorithm, diffuse and specular component are also calculated.



(a) (b)

Fig. 3. GUI of IV visualization system as a module of 3D Slicer: extensibility and functionality. (a) procesing pipeline (b) IV rendering module in 3D Slicer

The ratio between weight coefficients of each component defines the nature of reflection. We expect the proposed IV rendering result to have superior depth perception compared to original algorithm, in trade-off with calculation time.

2.3 GUI

We developed IV visualization system user interface as an extension module of open source image processing software (3D Slicer[6]). The advantage of this approach is that it is easy to combine it with existing features and modules of 3D Slicer, and therefore it is easy to build various surgery navigation applications. The IV rendering module follows data processing pipeline of 3D Slicer by using MRML data node (Fig 3). IV rendering module takes vtkMRMLScalarVolumeNode as input, so any 3D image will be dealt with the same way. Any volume node that is inputed into IV rendering module will be observed for update so that any change to the volume node will trigger an IV rendering cycle. In visualization of 3D ultrasound data, IV rendering module is used in combination with OpenIGTLink module[7]. OpenIGTLink module receive 3D data in real-time from other application (in this case, 3D ultrasound data acquisition software), and keep it in 3D Slicer memory as a vtkMRMLScalarVolumeNode, such that when inputed into 3D Slicer it will result in real-time visualization of IV stereoscopic image. Other features such as thresholding, ROI clipping were also implemented. And also, there is an option to enable automatic rendering performance control. If enabled, step size in ray tracing is automatically adjusted to match desired rendering frame rate.

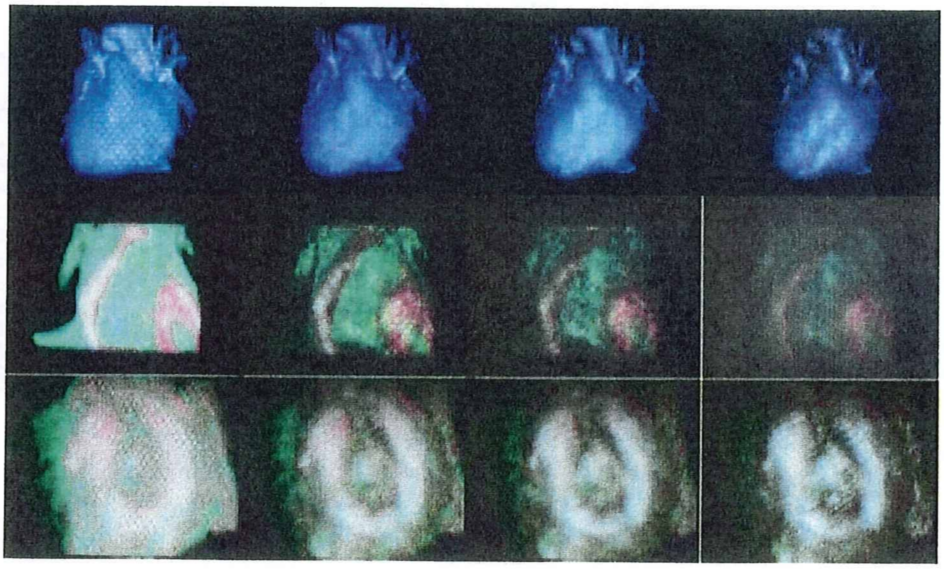


Fig. 4. IV stereoscopic visualization of various datasets using different shading parameters. top to bottom: CT data of human heart, MRI data of human heart, ultrasound data of porcine heart (mitral valve only). Left to right: IV rendering result with various shading parameter, Ambient:Diffuse:Specular = 1:0:0(original algorithm), 0.16:0.84:0, 0.08:0.75:0.17, 0.08:0.5:0.42.

2.4 Implementation Issues

Calculations of 3D ultrasound data transformation and IV rendering were implemented on GPU calculations using CUDA programming platform[8]. The workstation has an internal GPU for calculation and visualization (Quadro FX 5800, NVIDIA), and an external GPU computing server for calculation (Tesla D870, NVIDIA). To avoid resource usage timing conflict, 3D ultrasound data transformation and IV rendering were calculated on separate GPU. 3D ultrasound data transformation was performed on external GPU computing server, while IV rendering was performed on internal GPU.

3 Results

3.1 IV Image Quality Comparison

We compared IV image quality of the new IV rendering algorithm (composite rendering with Phong shading) with the original algorithm (composite rendering without shading). Targetting applications for heart surgery, We tried visualization on various datasets: CT, MRI, and ultrasound datasets. Visualization was compared between various shading parameters (Fig 4). In Fig 4, we put more weight on specular and diffuse components gradually from left to right. The CT

Table 1. Average calculation time of IV volume rendering

Data size	Composite (ms)	Composite with shading (ms)	% slower
64^3	23	23	0%
128^3	36	39	8%
256^3	59	77	31%
512^3	164	245	49%

screen size: 1024 × 768 pixels (n=100)

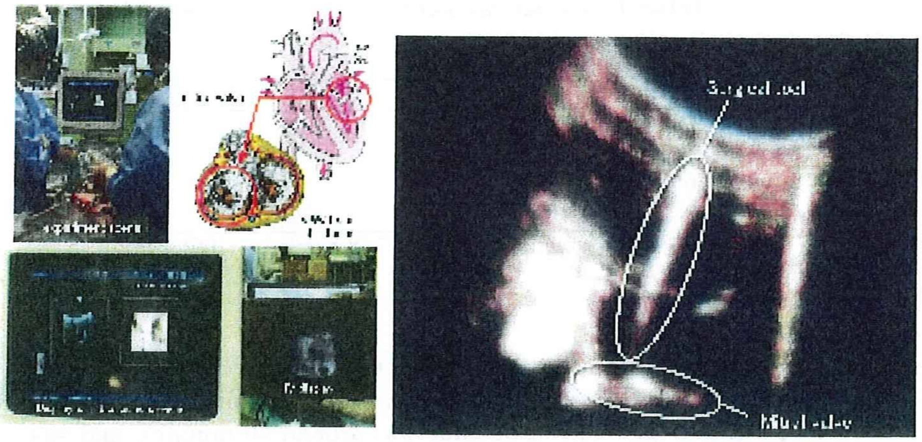
dataset was acquired using single slice CT with ECG gating. CT data size is 512 × 512 pixels ×192 slices. MRI dataset was acquired using 0.2T MRI with heart pulse gating. Acquisition time was around 40 minutes, and since we did not perform respiratory gating, the MRI data was rather noisy due to motion artifacts. MRI data size is 256×256 pixels ×19 slices.Ultrasound dataset was acquired with mechanical 3D convex probe, with data size of 304 × 248 pixels ×44 slices and data acquisition rate of 3 volumes/s. In case of low noise CT-dataset, shading is smooth, and the more specular component put on, the better the depth perception. In case of rather noisy datasets of MRI and ultrasound data, too much weighing on specular component may result in decrease on overall image brightness and contrast.

3.2 Rendering Time Evaluation

We evaluated IV rendering time of the new IV rendering algorithm (composite with shading) compared with the original algorithm (composite) for various data sizes (Table 1). For small data size, the new algorithm perform as fast as the original algorithm, but for big data size the new algorithm is up to 49% slower than the original algorithm.

3.3 In-vivo Experiment

To demonstrate the usefulness of IV surgery navigation system, we performed an in-vivo porcine(male, 47.5 kg) experiment simulating a mitral valve surgery on beating heart navigated by IV images of 3D ultrasound (Fig 5(a)). The surgery was conducted by expert cardiologist. The most important requirement to use the IV system in heart surgery is that it should be fast enough to follow heart beat movement. Therefore, in this experiment, firstly we tested IV system to visualize mitral valve movement in real-time. 3D ultrasound data acquisition was performed for several combinations of resolution and data acquisition rate, up to 8 volumes/s. Acquired 3D ultrasound data is in polar coordinate system and then transformed into rectangular coordinate system before being used for IV rendering. For all cases, 3D ultrasound data is transformed into 256 × 256 × 256 voxels data, which is rendered at around 13 fps, therefore IV rendering frame rate was still faster than data acquisition rate. So there was no frame skipping



(a) (b)

Fig. 5. In vivo porcine experiment: (a) Real-time IV stereoscopic image from intra-operative 3D ultrasound as image guidance. (b) simulating mitral valve surgery on beating heart, surgical tool was driven towards mitral valve under IV stereoscopic image guidance.

and time lag was less than 1 frame. Then, we guided a surgical tool towards mitral valve under 3D ultrasound guidance displayed as stereoscopic images on IV display (Fig 5(b)). For this first trial, we did not put any efforts on manipulator coating or by using manipulator with special material suitable for ultrasound data acquisition. With optimal rendering parameter setting, manipulator was seen clearly along with the beating heart, and it is easy to guide the manipulator towards mitral valve, and perform some surgery manipulations. According to the cardiologist conducting the surgery, time lag was within tolerable range.

4 Discussions

The use of Phong shading for IV rendering improved overall depth perception and image quality. However, based on imaging modality used, it is required to use modality specific shading parameters. For rather noisy datasets, smoothing on image gradient may improve shading quality. Decrease in performance was more significant for large dataset. The reason is that overall rendering time includes data transfer time between GPU and CPU that scales up with the number of voxels processed. In-vivo experiment showed that our system is feasible to guide open-chest beating heart surgery with 3D ultrasound. Our system is comparable with similar systems[9, 10] in terms of using real-time intra-operative images for guiding intra-cardiac beating heart surgery. Linte used 2D ultrasound augmented with pre-operative 3D CT image, while Li used 3 slices of real-time MRI images. Our system, using auto-stereoscopic 3D ultrasound images, should be the most intuitive among the three, and surgeries with fast moving target, such as mitral valve surgery should benefit the most from our system.

5 Conclusion

We have built a real-time autostereoscopic surgery navigation system with intraoperative data acquisition using 3D ultrasound. Implementation of Phong shading algorithm for IV has improve image quality and depth perception significantly. Performance decrease due to implementation of shading algorithm is less than 50%. It is still considerably fast enough to visualize 512^3 datasets in real-time. We also built GUI for IV visualization in modular design, so that it is straight-forward to combine it with various surgery navigation applications built on 3D Slicer. Clinical feasibility study on porcine phantom simulating open chest surgery showed that our system provide enough speed and image quality to guide beating heart surgery. In the future, we plan to use our system for wide range of applications, especially surgeries with large organ movements and deformations such as beating heart surgery and fetus surgery.

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