08(VI)-26

# 超高感度カメラを用いた低照度・低温胎児鏡の基礎検討

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# Light-saving Endosurgical intervention using ultrasensitive HARP camera

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**Abstract:** We developed a new endoscope to perform much less invasive surgical intervention within the dark intrauterine environment. As is well known, fetuses naturally grow and mature within the entirely dark uterine cavity. Currently, to observe the fetal patient, current fetoscope must employ an intense illumination that might adversely affect fetal ocular development along with fetal metabolic alterations due to a temperature rise in the amniotic fluid. Then, we should hopefully minimize the fetoscopic illumination during fetal intervention. Our fetoscope is equipped with a specifically designed camera using ultrasensitive HARP pickup tube enabling us to observe the fetus *in utero* with little extrinsic illumination. Using an anesthetized rabbit, a prototype fetoscope was used to observe the visceral blood vessels under low illumination environment or only making use of a flashlight located outside the peritoneal cavity. As a result, we could successfully obtain an intraperitoneal view either way. The outcome seems quite encouraging in terms of achieving much less invasive fetoscopic procedures.

**Key words:** Computer aided surgery, Fetal surgery, Fetoscope, HARP, Ultrasensitive camera

## 1. はじめに

胎児は生理的に外部光から完全に遮断された子宮内で成長するが, CCD (Charge Coupled Device) イメージセンサを適用した現状の内視鏡では, 胎児を観察する際に子宮内に強い光を照射しなければならず, 羊水温の上昇をもたらす可能性があるとともに, 胎児に負の影響(胎児視覚器の発達阻害や代謝変動など)を及ぼすリスクがある[1][2]. 一方, 近年CCDに比べ格段に高い感度を有し, わずかな照明でノイズの少ない鮮明な映像が得られるHARP (High-gain Avalanche Rushing amorphous Photoconductor) イメージセンサの開発が進んでいる[3].

今回, 我々は, 子宮内手術にも応用可能な“低照度・低温胎児鏡”の開発に向け, 超高感度HARP撮像管を搭載した内視鏡にて家兎の腹腔内観察を行い, 現状に比べて格段に少ない照射光量で内視鏡観察が可能であることを確認したので報告する.

## 2. 方法

放送用の超高感度HARP撮像管カメラ(厚さ15μmのHARP膜を使用)と放送用CCDカメラとに, 外径φ5.4mmの硬性内視鏡を, 今回開発したアダプタ(接続光学系)を介して接続し, 撮像評価を行った.

### 2.1 胎盤ファントムの観察

暗室の中で, 胎盤ファントムの撮影を行った(**Fig. 1**). 内視鏡の先端部から胎盤ファントムまでの距離は30mmである.

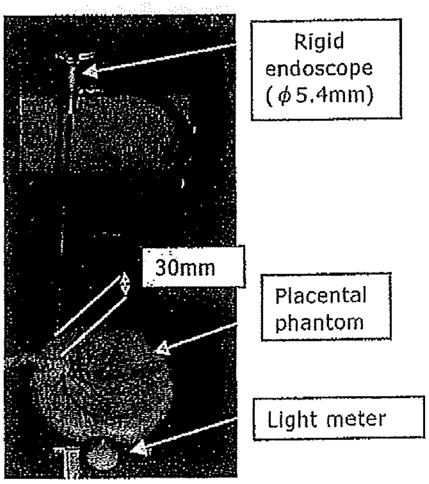


Fig. 1 Placental phantom imaging in a dark room.

### 2.2 低照度環境下での家兎腹腔内観察

麻酔を施した白色家兎の腹腔内を観察した．本実験では，内視鏡のライトガイドを通して白色家兎の腹腔内に照射される光量を減らし，HARP 撮像管と CCD で得られた映像を比較評価した．

### 2.3 体外照明下での家兎腹腔内観察

麻酔家兎の腹腔に本内視鏡を挿入し，手術室内無影灯や内視鏡自体の光源による照射を行うことなく，家兎体外からの懐中電灯による光のみを照射し，内臓・腸間膜血管の観察を試みた．

## 3．結果

胎盤ファントムの撮像結果を示す(**Fig. 2**)．被写体照度は約 100lx（通常の内視鏡では，照度約 10 万 lx 以上）であった．HARP 撮像管では低照度環境下においても胎盤ファントムの観察が十分可能であることが判明した．家兎の腹腔内観察の結果(**Fig. 3**)では，内臓血管などの識別が十分可能であった．懐中電灯を家兎の体外から照射した場合でも(**Fig. 4**)，CCD に比べノイズのより少ない鮮明な映像を得ることができた．

## 4．考察

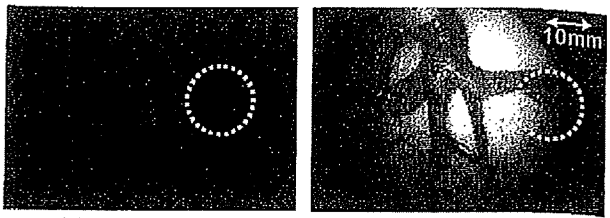
胎盤ファントムの撮像実験では，特に画像の辺縁部において，HARP 撮像管を用いた場合と CCD を用いた場合に顕著な差がみられた．即ち，暗部では CCD と比べて HARP の優位性が高いといえる．

家兎腹腔内観察では，HARP 撮像管にて内臓・腸間膜血管を識別することが可能であり，既存の CCD に比べ照射光量を格段に減らせることがわかった．懐中電灯による体外照明の場合，内視鏡装置に接続する通常2本のケーブル（画像伝送用，光源用）のうち光源用のものが不要となるため，内視鏡の操作性向上，手術時間の短縮や医師の負担軽減も期待される．さらに，胎児や母体への侵襲が少ない細径内視鏡，即ち“低照度・低温内視鏡”実現の可能性も示唆される(**Fig. 5**)．

## 5．まとめ

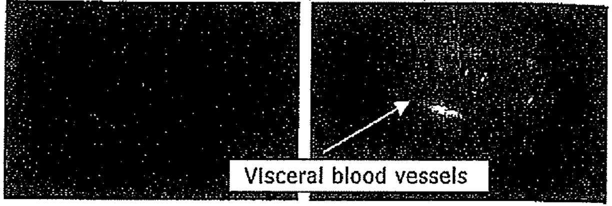
内視鏡に超高感度 HARP 撮像デバイスを搭載することで，わずかな光（あるいは外部照明のみ）を照射するのみで鮮明な映像の得られることが判明し，低侵襲の子宮内観察や胎児治療などに不可欠な“低照度・低温内視鏡”の開発に見通しをつけることができた．この結果を受けて，我々は現在，HARP 撮像管に比べて飛躍的に小型な次世代超高感度イメージセンサ“FEA（Field Emitter Array）-HARP”と，これを用いた“低照度・低温内視鏡”の開発に取り組んでいる．

謝辞：本研究の一部は，経済産業省インテリジェント手術機器研究開発プロジェクト「研究連携型機器開発」，並びに厚生労働科学研究費補助金医療機器開発推進研究事業（H20-ナノ-一般-016）による．



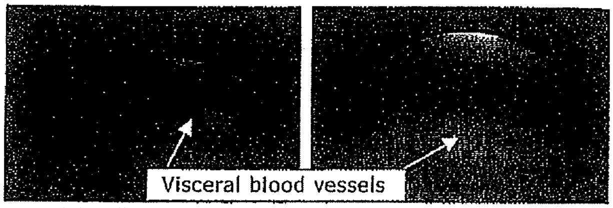
(a) CCD camera (b) HARP camera

**Fig. 2** Placental phantom images in a dark room with low illumination (100lx in light intensity).



(a) CCD camera (b) HARP camera

**Fig. 3** Rabbit's intraperitoneal images with low illumination.



(a) CCD camera (b) HARP camera

**Fig. 4** Rabbit's intraperitoneal images with a flashlight located outside the peritoneal cavity.

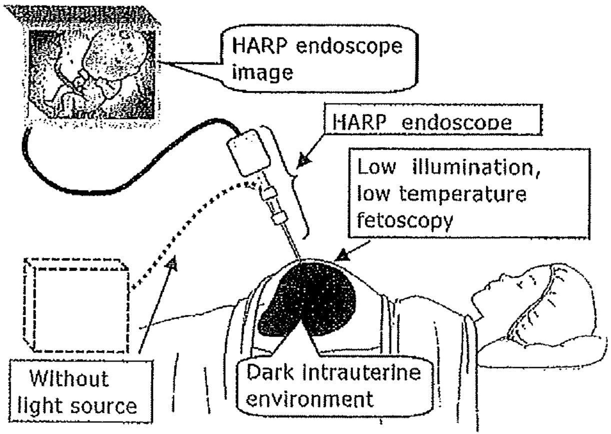


**Fig. 5** Low-illumination, low-temperature fetoscope.

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# 子宮内手術にも応用可能な"低照度・低温内視鏡"の開発に向けて

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【背景・目的】胎児は、外部光から完全に遮断された子宮内で成長するが、CCD(Charge Coupled Device)イメージセンサを適用した現状の内視鏡では、胎児を観察する際に子宮内に強い光を照射しなければならず、羊水温上昇の可能性とともに、胎児に負の影響を及ぼすリスクがある。一方、近年、CCDに比べて、格段に高い感度を有し、わずかな照明で鮮明な映像が得られるHARP (High-gain Avalanche Rushing amorphous Photoconductor) イメージセンサの開発が進んでいる。今回、超高感度なHARP撮像管を適用した内視鏡による家兎の腹腔内観察実験を行ったので報告する。

【方法】放送用の超高感度HARP撮像管カメラとCCDカメラとに硬質内視鏡を接続し、麻酔家兎の腹腔内を観察した。内視鏡のライトガイドを通して家兎の腹腔内に照射される光量を減らし、HARP撮像管とCCDで得られた映像を比較評価した。また、併せて、家兎の体外から懐中電灯による光のみを照射し、内臓・腸間膜血管の観察を試みた。

【結果】HARP撮像管では低照度の環境下においても家兎の内臓血管などの識別が十分に可能で、既存のCCDに比べて、照射光量を格段に減らせることがわかった。また、懐中電灯による光を家兎の体外から照射した場合においても、CCDに比べてノイズの少ない鮮明な映像が得られた。後者の結果は、操作性に優れ、かつ、母胎への影響も少ない光源レス細径内視鏡の実現可能性を示唆するものとして重要である。

【結論】内視鏡に超高感度なHARP撮像デバイスを適用することで、低照度で鮮明な映像が得られることがわかり、低侵襲な胎児治療などに不可欠な"低照度・低温内視鏡"の開発に見通しを得ることができた。ここでの結果を受けて、現在、我々は、HARP撮像管に比べて飛躍的に小型な次世代超高感度イメージセンサ"FEA(Field Emitter Array)-HARP"と、これを適用した"低照度・低温内視鏡"の開発に取り組んでいる。

# Night-vision fetoscope

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We developed a new endoscope, the "night-vision fetoscope" to perform much less invasive surgical intervention within the dark intrauterine environment. As is well known, fetuses naturally grow and mature within the entirely dark uterine cavity. Accordingly, to observe the fetal patient, current fetoscope must employ an intense illumination that might adversely affect fetal ocular development along with fetal metabolic alterations due to a temperature rise in the amniotic fluid. Then, we should hopefully minimize the fetoscopic illumination during fetal intervention. Our night-vision fetoscope is equipped with a specifically designed camera using a miniaturized ultrasensitive HARP (High-gain Avalanche Rushing amorphous Photoconductor) enabling us to observe the fetus *in utero* with little extrinsic illumination.

Using an anesthetized rabbit, a prototype of the night-vision fetoscope was tested for observing the visceral blood vessels without laparotomy. Strikingly enough, we could successfully obtain an intraperitoneal view just making use of a flashlight located outside the peritoneal cavity.

In conclusion, the outcome seems quite encouraging in terms of achieving much more physiological fetoscopic procedures.

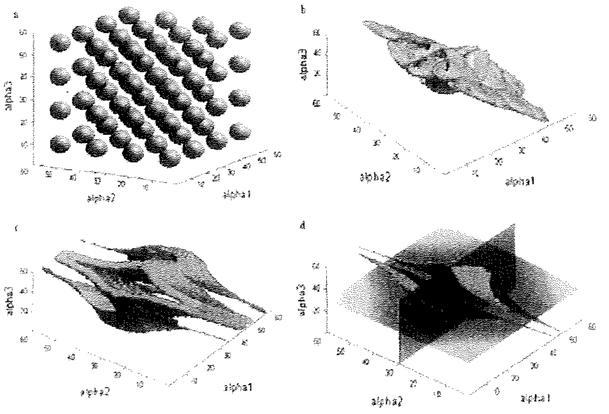

**Fig. 3** (a) Automatic 3D seed initialisation of the level set. (b) The zero level set during the evolution. (c) The narrow band around zero level set. (d) The final zero level set

data sets. The remaining variation was analyzed by PCA (Figure 2). We retain the first three principal components, which account for 89.22% of shape variability in the population. In our case, we use the range $-3 \le \alpha_i \le 3$ for every shape coefficient. This accounts for 99.7% of the shape variability encompassed in each principal component. We generate a scalar 3D map by computing the difference between the anteversion angles of the mean femur shape and the generated instance shape. We do not need to explicitly compute $\mu$ for every point in the shape space, but only in a narrow band around the zero level set, to reduce computational burden. Finally, the segmented area gives the set of shapes that have a similar range of anteversion angle (Figure 3). This information can then be used by implant manufacturers to determine the best implant design to fit most of the population.

### Conclusion

The method for optimisation in PCA shape space allows to find a partition of the shape distribution into regions that meet / do not meet a given criterion. Illustrative results have been shown for anatomical analysis of femora. Although the example has been elaborated for 3D maps (i.e. taking only 3 principal components), the method is applicable to maps of any dimension, determined by the number of principal components retained. To our knowledge, this is the first research into the problem of finding all instances in a shape distribution meeting a given criterion. The practical use of such a concept is of extreme importance in the study of the anatomical evidence of a pathology, or the morphologic features in implant positioning.

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## Interactive Autostereoscopic Medical Image Visualization System using GPU-accelerated Integral Videography Direct Volume Rendering

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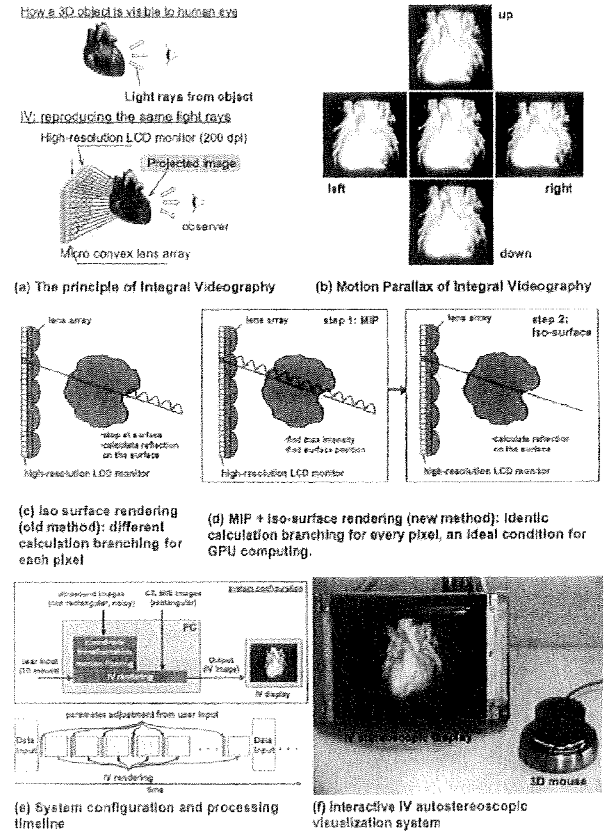
### Keywords

Integral videography, Stereoscopic image, Volume rendering

### Purpose

In the development of 3D medical imaging, 3D image acquisition has reached the level that it is relatively easy to acquire 3D images of the human body. Medical imaging modalities such as MRI, CT, and Ultrasound have been able to provide 3D images needed for diagnostics and therapies. Acquired 3D images are usually displayed on 2D screen. While this visualization method is quite useful for diagnosis, it may not be enough for surgical navigation, where depth perception is very important. So it is required to display 3D images on 3D screen, as a stereoscopic image. One of the stereoscopic imaging methods is Integral Videography (IV), an autostereoscopic imaging



(a) The principle of Integral Videography

(b) Motion Parallax of Integral Videography

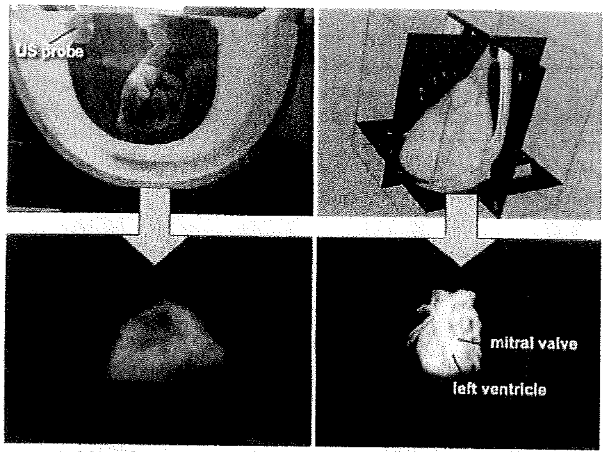
(c) Iso surface rendering (old method): different calculation branching for each pixel

(d) MIP + iso-surface rendering (new method): identic calculation branching for every pixel, an ideal condition for GPU computing.

(e) System configuration and processing timeline

(f) Interactive IV autostereoscopic visualization system

Fig. 1



a IV image from ultrasound image

b IV image from CT data (with slicing)

Fig. 2

method that projects light rays into 3D space using the combination of high-resolution display and convex lens array that is placed in front of the display (Fig. 1(a)), so that IV has motion parallax (Fig. 1(b)). Compared to other stereoscopic imaging method such as binocular stereoscopic, IV has advantages that it does not need glasses or other viewing devices, it is spatially accurate, and it allows multiple spectators at the same time. Because of that, IV is said to be a suitable imaging method for use in clinical situation. However, IV rendering process, the process of creating IV image from a 3D image, is a computationally heavy process. It was not possible to render IV images in real-time manner, and therefore real-time user interactivity was not possible either. The purpose of this paper is to develop an interactive IV stereoscopic medical image visualization system. In details, we developed a GPU-accelerated real-time direct volume rendering method, and realized real-time user interactivity. Then we applied our system for some clinical studies on ultrasound data and CT data.

### Methods

The system consists of a processing PC with GPU, a 3D mouse as input device, and an IV stereoscopic display (Fig. 1(e)). As IV rendering method, we implemented direct volume rendering based on ray-tracing method on NVIDIA Compute Unified Device Architecture (CUDA) as GPU programming platform. We used CUDA-compatible NVIDIA GeForce 8800 GTX as the GPU. For calculations on GPU to be optimum, an identical calculation branching for all calculations is required. Therefore, instead of using previous iso-surface rendering method (Fig. 1(c)), we developed a new ray tracing method by combining MIP rendering and iso-surface rendering (Fig. 1(d)). By finding surface position while doing MIP rendering, we can directly calculate reflection on the surface in iso-surface rendering, and thus ensure identic calculation branching for every pixels. Combining the result of both ray tracing methods also enable opacity control. The proportion of iso-surface rendering defines opacity, where 0% iso-surface rendering means totally transparent and 100% iso-surface rendering means totally opaque. We enabled our system to handle rectangular data set (MRI, CT) and non-rectangular data set (ultrasound). In case of non-rectangular ultrasound data, we performed coordinate transformation and median filtering as preprocessing, which were also performed on GPU. Interactive user interface was realized using a 3D mouse with 6 DOF and 2 input buttons (SpaceNavigator, 3dconnexion). If the rendering process is fast, user interactivity will become possible because now we can put multiple rendering cycles in between data input process. By adjusting rendering parameters before each rendering cycle, real-time manipulation is possible (Fig. 1(e)). In this system, we realized real-time translation, rotation, data slicing, and threshold adjustment for maximum user experience. The Figure 1(f) shows the interactive IV image visualization system, that consists of a 3D mouse as the input device and an IV autostereoscopic display as the output device. As clinical studies, we applied our system for IV stereoscopic visualization from ultrasound and CT data.

### Results

We evaluated the IV rendering speed by comparing IV rendering performances on CUDA compared to that on CPU (Pentium D 3.2 GHz). Rendering time was calculated for both architectures for various 3D data sizes. IV rendering average frame rate using GPU was 125, 59, 15, 2.5 fps compared to 4.2, 1.6, 0.3, 0.04 fps using CPU respectively for data size of $64^3$, $128^3$, $256^3$, $512^3$ voxels. GPU-accelerated IV rendering using CUDA outperformed CPU rendering by scale factor of 30 to 63 times for the data size tested. It was observed that the bigger the data size, the higher the scale factor. This is because rendering process using GPU also included data transfer between CPU and GPU, and only the calculation time but not the data transfer time scales up with size. Because the data size of IV image remains the same for all data sizes, it contributes a lot to smaller data and become more negligible for larger data. As clinical study, we used our system to visualize 4D ultrasound data in real-time manner (Fig. 2(a)). For the case of ultrasound data (64 × 64 × 64 voxels), coordinate transformation and median filtering time was 1.7 ms and 13 ms on GPU, compared to 14 ms and 60 ms on CPU, which means about 8 and 5 times improvements respectively. Overall average frame rate of the system was 29 fps using GPU acceleration compared to 2 fps without GPU acceleration. Then we also used our system to observe mitral valve from 3D CT data (512 × 512 × 190 voxels). Overall average frame rate was 5.3 fps. User interactivity with data slicing and opacity adjustment function made it easy for user to find and observe mitral valve inside the heart (Fig. 2(b)).

### Conclusion

We have developed an interactive IV stereoscopic medical image visualization system by enabling real-time IV rendering through GPU acceleration. We also successfully realized user interactivity for IV visualization system. Clinical studies have shown that our system is capable to provide a real-time visualization and manipulation of various medical image data seamlessly. Applying this system on various IV surgery navigation system applications is our future plan in computer-aided surgery.

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## Calibration method for electromagnetic tracked instruments in clinical applications

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**Keywords** Calibration, Electromagnetic tracking, Computer guided surgery

### Purpose

We present a method for calibration of an electromagnetic tracked tool integrated into a previously developed navigation system for head and neck surgery. The method considers application specific sources of errors. Due to the distance between the field generator and sensors, incident angle between sensors and field generator and presence of metal errors in the measured position and orientation may be present. Furthermore, the dynamic behaviour of the system, that is, natural movements of the sensors attached to the tool, introduces errors.

To reduce the deviation in the position, data from the magnetic tracker should be corrected before displayed. The method used in this work is lookup-table (LUT), which stores "true" values in a table corresponding to specific locations and poses of the tool in order to

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# Integral Videography立体像表示システムのユーザインターフェースの開発

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# Development of User Interface for Integral Videography Autostereoscopic Image Visualization System

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**Abstract:** This paper presents a user interface for Integral Videography (IV) auto-stereoscopic visualization system. We developed IV visualization system as a module of open-source medical image processing software 3D Slicer. In order to be able to completely integrated into 3D slicer, we added some functionalities into IV rendering algorithm, such as Z-buffer support, multi data type support, and camera model. Interactive user interface was realized to allow user to change rendering parameters such as rendering algorithm, interpolation method, color and alpha transfer function. We also made our IV rendering module to interact smoothly with OpenIGTLink module, that allows real-time visualization of real-time 4D image data, and ability to track position and orientation of surgical tools or images. As an example application, we use a 4D ultrasound simulator that send real-time 4D images to 3D Slicer through OpenIGTLink framework. We confirmed that real-time image datasets with the size of 256x256x256 voxels and 5 fps of data acquisition rate can be visualized smoothly with our system.

**Key words:** Integral Videography (IV), user interface, 3D Slicer

## 1. 序論

医用画像の発展では，三次元・四次元画像を比較的容易に取得できるようになった．それらの画像を診断・治療に活用するために，表現力の高い表示方法が望まれる．特に治療では，奥行き情報が大事であり，立体像表示のような直感的な画像表示方法が有効であると考えられる．

立体像表示方法として，以前からIntegral Videography(IV)[1]を開発してきた．IVは，高解像度液晶ディスプレイ及び凸レンズアレイの組み合わせで，液晶ディスプレイからの光を凸レンズアレイにより三次元空間上に投影され，空間上に位置・姿勢を正確に表現できる立体像表示方法であり，患者さんに重ね合わせ表示いわゆるAugmented Realityが可能である．また，IVはメガネなどの装着が不要で，複数人に同時に観察可能などの利点が挙げられ，医療現場に最適であると考えられる．今までのIVの研究の中で，色や透明度の表現ができるIV画像を作成アルゴリズムやGPU処理を用いたリアルタイムIV画像の研究[2]が行われ，手術誘導に必要とされている基礎技術が揃っていると言える．

開発したそれらの基礎技術を臨床応用に導くためには，臨床現場のニーズに合わせたユーザインターフェースの開発も必要不可欠である．色々な手術の応用を考えると、多機能・拡張性の良いユーザインターフェースが望まれる．

本研究では，そのIV立体像表示システムのユーザインターフェースを開発することを目的とする．具体的には，多機能・拡張性の良いユーザインターフェースを目指し，3D SlicerのモジュールのIV立体像表示モジュールの開発を行う．

## 2. 方法

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[3]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．

あらゆる断層面で三次元画像を切ったIV立体像の表示も考慮して，IV立体像モージュルは3D SlicerのvtkMRMLVolumeNode及びvtkMRMLTransformNodeを入力として用いる．vtkMRMLVolumeNodeは視覚化したい三次元データを表し，vtkMRMLTransformNodeは断層面の位置・方向を表す．IV立体像パラメタは以下のものがユーザ入力から設定される．

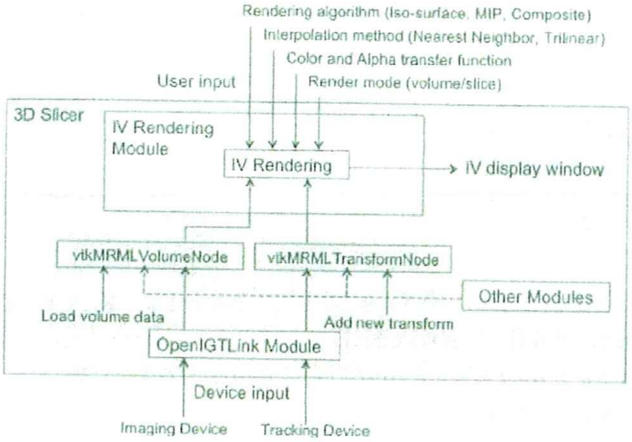

Fig.1 IV rendering module software configuration

- IVレンダリングアルゴリズム(Iso-surface/MIP/Composite)
- 補間方法(Nearest Neighbor/Trilinear)
- 色と透明度のマッピング
- 表示モード(ボリューム/スライス)

また，3D Slicerに完全に統合できる用にするために，IV画像作成アルゴリズムに以下の機能を追加した．

- マルチデータタイプに対応化
- Z-Buffer
- VTKのカメラモデルに対応化

また，応用例としてOpenIGTLinkモージュルと組み合わせ，以下のことも考えられる．

- リアルタイムで四次元画像をIV立体像として表示する．OpenIGTLinkモジュールが四次元画像を受け取ってvtkMRMLVolumeNodeを更新しながら，一方で，IV立体像表示モジュールが更新された画像を基にリアルタイムでIV画像を更新する．
- 手術器具・画像・オーバーレイディスプレイをトラッキングする．OpenIGTLinkモジュールは行列を受け取って3D Slicerのあらゆるvtk MRMLTransformNodeを更新しながら，行列の更新ごとにIV立体像が更新する．

## 3．結果・考察

開発したユーザインタフェースはFig.2に示す．IVディスプレイとして，6.4” XGA (200 dpi)の液晶モニタを使用した．処理速度は三次元データのサイズ・複雑さやレンダリングアルゴリズム・パラメタにより大きく変わるが，256x256x256 voxelsの三次元データを平均15 fpsの更新速度で表示可能である．

応用例として四次元超音波超音波画像をリアルタイムで取得しながらIV立体像で表示するようなアプリケーションを考えて動作確認実験を行った．四次元超音波のシミュレータから OpenIGTLink を通して超音波データを3D Slicerに送リアルタイムIV立体像として表示する．本実験では，256x256x256 voxelsの三次元データを5 fpsの更新速度で問題なくスムーズに表示できると確認した．

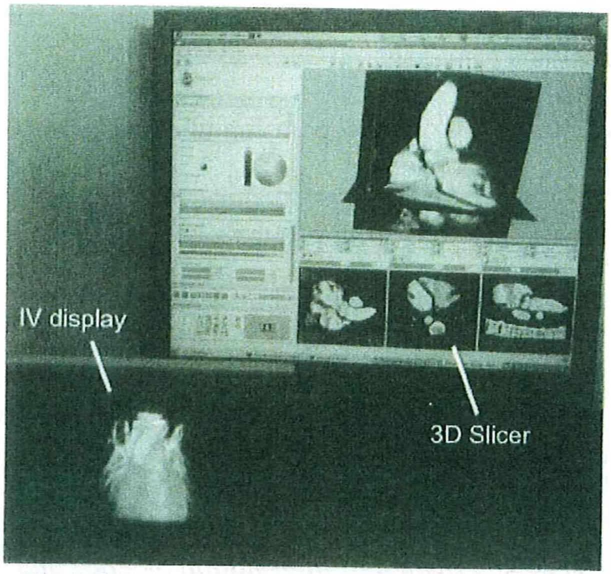

Fig.2 IV auto-stereoscopic visualization system with user interface

## 5．結論

3D SlicerのモジュールとしてIV立体像表示モジュールを開発したことにより，多機能・拡張性の良いIV立体像表示のユーザインターフェースを実現した．また，OpenIGTLinkと連携させることにより，四次元データの視覚化やトラッキング機能も使用できると動作確認した．今後，臨床応用を目指して，臨床のニーズを考慮しながら機能・パフォーマンスを向上させたいと考えている．

本研究開発の一部は，日本学術振興会科学研究費補助金(17100008)及び(19・2984)と総務省戦略的情報通信研究開発推進制度(062103006)とNEDO技術開発機構産業技術研究助成事業(07C46054)による．

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3) 3D Slicerホームページ http://www.slicer.org

6.3

Title

# Light-saving fetoscope using ultrasensitive HARP camera

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Abstract

We developed a new endoscope to perform much less invasive surgical intervention within the dark intrauterine environment. As is well known, fetuses naturally grow and mature within the entirely dark uterine cavity. Currently, to observe the fetal patient, conventional fetoscope must employ an intense illumination that might adversely affect fetal ocular development along with fetal metabolic alterations due to a temperature rise in the amniotic fluid. Then, we should hopefully minimize the fetoscopic illumination during fetal intervention.

Our fetoscope is equipped with a specifically designed camera using ultrasensitive HARP (High-gain Avalanche Rushing amorphous Photoconductor) enabling us to observe the fetus in utero with little extrinsic illumination. In order to apply broadcast HARP camera to the fetoscope, we developed a new camera adaptor which can be connected to the fetoscope. Also, we developed a smaller camera (100mm in diameter and 2kg in weight), and a small fetoscope (4mm in diameter).

A prototype fetoscope was used to observe a resolution chart under low illumination environment. As a result, we could successfully observe a resolution chart. The outcome seems quite encouraging in terms of achieving much less invasive fetoscopic procedures.

[Acknowledgement] A part of this work is supported by “Health and Labour Sciences Research Grants: Research on Nanotechnical Medical” administrated by Ministry of Health, Labour and Welfare.

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09(XVII)-93

# 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．

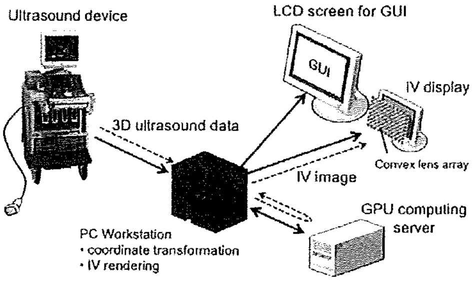

Fig.1 System configuration of real-time 3D ultrasound IV visualization system

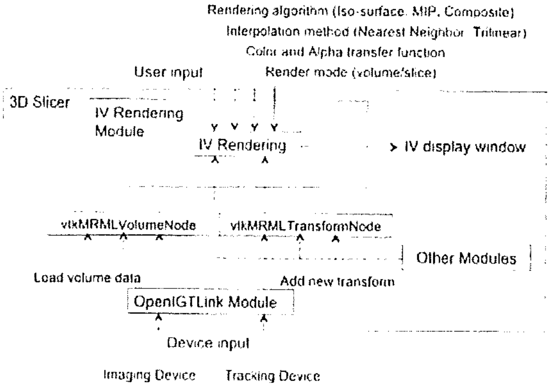

Fig.2 IV rendering module configuration

### 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ハ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

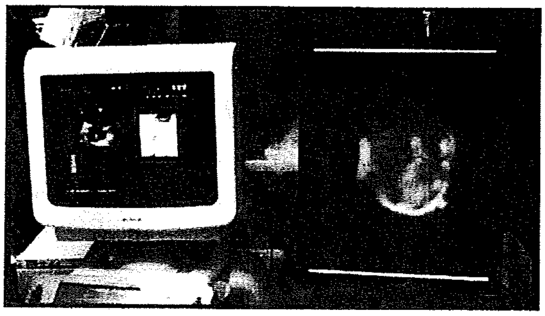

Fig.4 In-vivo experiment: IV visualization of 3D ultrasound image of porcine beating heart

## 謝辞

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4) 3D Slicerホームページ http://www.slicer.org

# 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($\alpha$10, 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

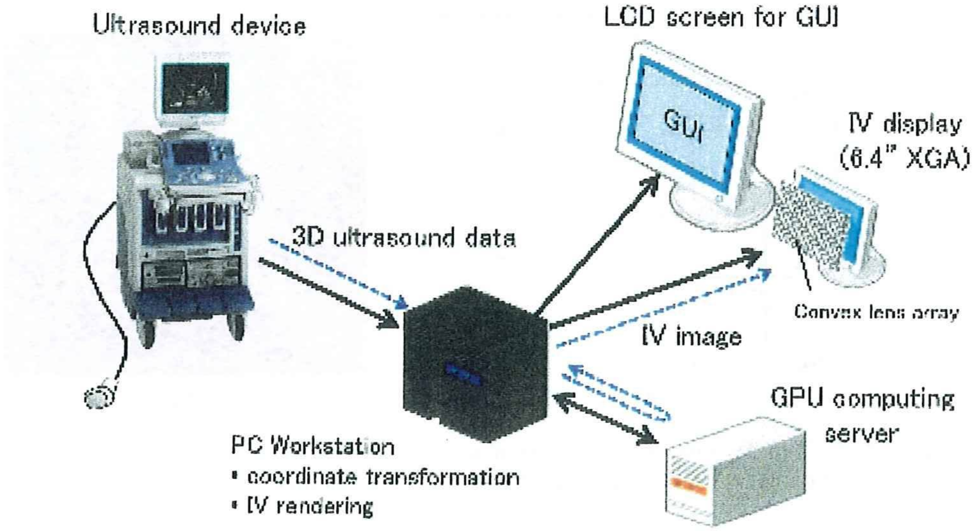


Fig. 1. System configuration.

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.

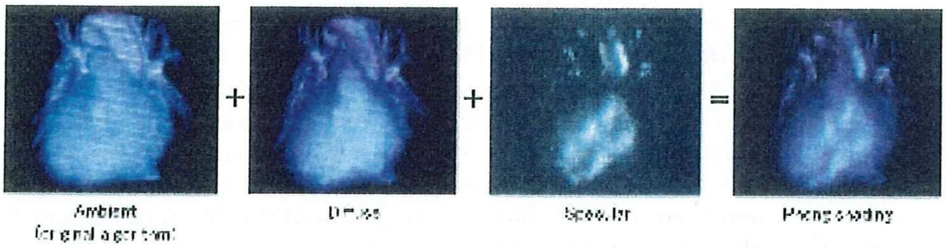
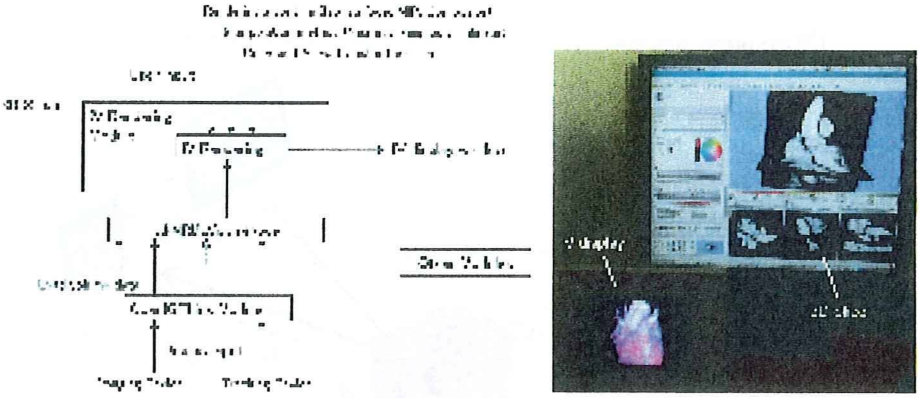


Fig. 2. Phong shading for IV stereoscopic image. In addition to ambient component of original algorithm, diffuse and specular component are also calculated.



(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.

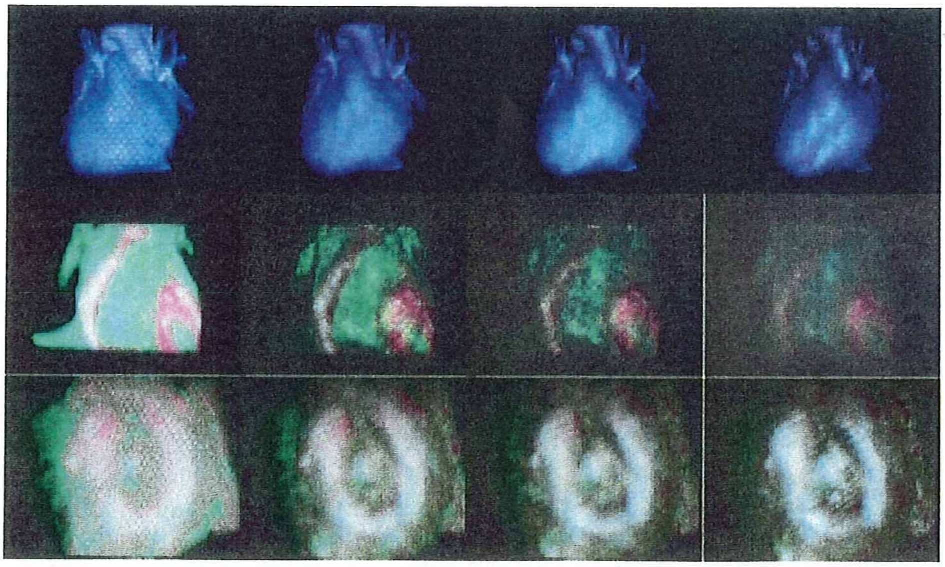


**Fig. 4.** IV stereoscopic visualization of various datasets using different shading parameters. top to bottom: CT data of human heart, MRI data of human heart, ultrasound data of porcine heart (mitral valve only). Left to right: IV rendering result with various shading parameter, Ambient:Diffuse:Specular = 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)

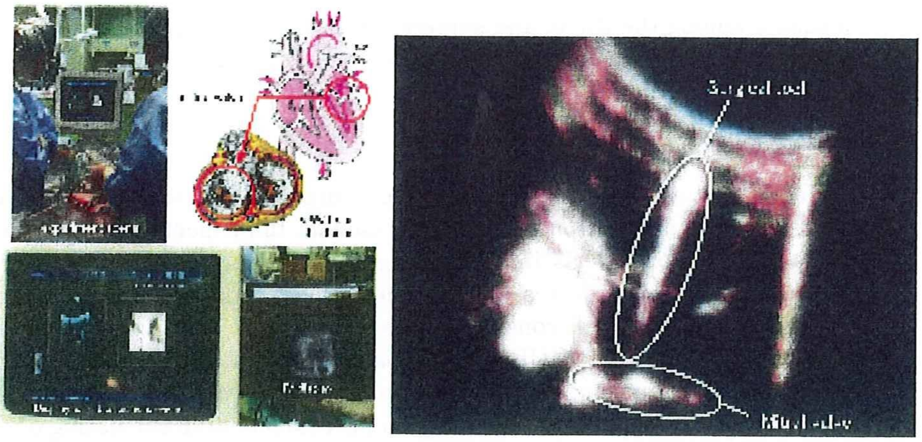
dataset was acquired using single slice CT with ECG gating. CT data size is 512 × 512 pixels ×192 slices. MRI dataset was acquired using 0.2T MRI with heart pulse gating. Acquisition time was around 40 minutes, and since we did not perform respiratory gating, the MRI data was rather noisy due to motion 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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