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Real-time computerized video enhancement for minimally invasive fetoscopic surgery

Praneeth Sadda [a, *], John Onofrey [b, c], Metehan Imamoglu [a, d, e], Xenophon Papademetris [a, b, c], Bilal Qarni [f], Mert Ozan Bahtiyar [a, d, e]

[a] *Yale University School of Medicine, USA*
[b] *Department of Radiology and Biomedical Imaging, Yale University School of Medicine, USA*
[c] *Department of Biomedical Engineering, Yale University School of Medicine, USA*
[d] *Department of Obstetrics and Gynecology, Yale University School of Medicine, 333 Cedar Street, New Haven, CT 06510, USA*
[e] *Yale Fetal Care Center, Yale-New Haven Hospital, 1 Long Wharf Drive, New Haven, CT 06510, USA*
[f] *University of Western Ontario, 1151 Richmond Street, London, ON N6A 3K7, Canada*

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ABSTRACT

Background: The only definitive treatment for twin-to-twin transfusion syndrome is minimally invasive fetoscopic surgery for the selective coagulation of placental blood vessels. Fetoscopic surgery is a technically challenging operation, mainly due to the poor visibility in the uterine environment. We present the design of an algorithm for the computerized enhancement of fetoscopic video and show that the enhanced video increases the ability of human users to identify blood vessels within fetoscopic video rapidly and accurately.
Methods: A computer algorithm for the enhancement of fetoscopic video frames was created. First, optical fiber artifacts were removed via a modification of unsharp masking. Second, image contrast was increased via Contrast Limited Adaptive Histogram Equalization (CLAHE). Third, the effect of contrast enhancements on stationary features was removed by normalizing to a windowed mean of the video frames. Fourth, color information was reincorporated by combining the mean-normalized result with the unnormalized contrast enhanced image using the soft light blending algorithm.
Medical trainees ($n = 16$) were recruited into a study to validate the algorithm. Subjects were shown enhanced or unenhanced fetoscopic video frames on a screen and were asked to identify whether a randomly placed marker fell on a blood vessel or on background. The accuracy of their responses was recorded.
Results: On the subset of images where subjects had the lowest mean accuracy in identifying the placement of the marker, subjects performed better when viewing video frames enhanced by the computer (accuracy 74.82%; SE 0.57) than when viewing unenhanced video frames (accuracy 63.78%; SE 2.79). This result was statistically significant ($p < 0.01$).
Conclusion: Real-time computerized enhancement of fetoscopic video has the potential to ease the readability of video in poor lighting conditions, thus providing a benefit to the surgeon intraoperatively.

1. Introduction

Twin-to-twin transfusion syndrome is a disease of monochorionic pregnancies in which abnormal anastomoses in the placental vasculature cause a net flow of blood from one twin fetus to the other.[1] When left unmanaged, it is associated with a high rate of morbidity and mortality. While there are multiple options for managing twin-to-twin transfusion syndrome, fetoscopic laser photocoagulation surgery is the only definitive treatment.[2]

In fetoscopic laser photocoagulation surgery, a fetoscope is introduced into the uterine environment via a transabdominal approach. The surgeon uses the fetoscope to inspect the placental vasculature and identify abnormal vascular formations. These formations are photocoagulated with a laser attached to the fetoscope.[2]

* Corresponding author. 123 York Street, New Haven, CT 06511, USA.
E-mail address: psadda@gmail.com (P. Sadda).

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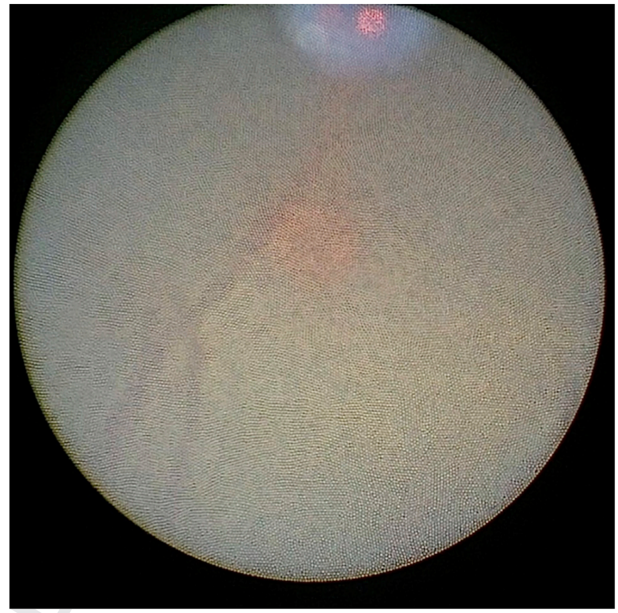

Fig. 2. A fetoscopic video frame that demonstrates the effect that the turbidity of amniotic fluid has on visibility in fetoscopic video. The discoloration of the amniotic fluid leads to poor contrast in the video frame which in turn makes it difficult to differentiate the blood vessel (which runs from the bottom left of the image to the top middle portion of the image) from the background.

Most minimally invasive surgeries revolve around the use of a laparoscope that acquires high-resolution video. However, the nature of fetoscopy requires a specialized fetoscope of a smaller diameter than a general-purpose laparoscope.[3] This reduces the maximum quality of the video that can be acquired through a fetoscope.[3] Furthermore, while most modern laparoscopes are lens-based, intraoperative video in fetoscopy is often acquired through a fiber optic endoscope. Optical fiber bundles are useful in fetoscopy because they allow for a curved approach, which is sometimes made necessary by positioning of the fetus relative to the placenta. Video acquired through optical fiber bundles, however, has a grid-like pattern of dark circular artifacts corresponding to the empty regions between adjacent fibers within the bundle (Fig. 1). These artifacts reduce the clarity of the video.

The limited quality of fetoscopic video is compounded by the poor visibility conditions within intrauterine environment: Amniotic fluid is cloudy and discolored, often with a yellow or greenish hue.[4] The cloudiness of the fluid reduces the maximum distance to which the surgeon's light source is able to penetrate. As a result, surfaces more than a few centimeters away from the fetoscope are often dark and indistinct. These effects are demonstrated in Fig. 2.

The net effect of these visual challenges is to make it difficult for the surgeon to quickly and accurately identify blood vessels during fetoscopic laser photocoagulation. In the worst case, these visual challenges could lead to the surgeon completely missing a subset of the problematic anastomoses and failing to ablate them, thereby necessitating a follow-up surgery.

Given the number of visual challenges present in fetoscopy, we believe that a computerized system for enhancing fetoscopic video can make the video clearer and more easily interpretable, thus providing a benefit to both the surgeon and the patient.

There has been relatively little prior research into the computerized enhancement of laparoscopic video given the high quality of video acquired from general-purpose laparoscopes. There have been many applications of computerized image enhancement in other medical domains, however. Contrast enhancement, for example, has been used to increase the readability of radiologic images such as mammograms and chest CTs.[5,6]

There has also been research into methods for the computerized enhancement of endoscopic images and optical coherence tomography images,[7,8] which, like fetoscopic images, can be acquired through optical fiber bundles.

While contrast enhancement and optical fiber artifact removal have been used to enhance images in a variety of other medical domains, to the best our knowledge there is no existing work that has demonstrated the applicability of these existing methods to fetoscopy. In this work, we present the design of a computer algorithm for enhancing fetoscopic video, demonstrate that the algorithm is fast enough for real-time use, and demonstrate that the enhancement of video has positive effects on the ability of humans to quickly and accurately identify blood vessels in fetoscopic video.

2. Materials and methods

2.1. Optical fiber artifact removal

To remove optical fiber artifacts from the video, we exploit the following observations:

1. The optical fibers in the video are of a fixed size.
2. The optical fibers are smaller than any of the relevant anatomy within the laparoscopic image—a single blood vessel spans several optical fibers.

Fig. 1. Left: A zoomed-in detail of a small portion of a fetoscopic video frame that demonstrates the presence of optical fiber artifacts. The small dark areas in the image correspond to gaps in between the fibers of the optical fiber bundle. Right: The same region after the removal of optical fiber artifacts via the method described in this article.