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Two- and three-dimensional high-resolution imaging of the human oviduct with optical coherence tomography

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Objective: To evaluate the feasibility of optical coherence tomography, a new method of micron-scale imaging, for high-resolution assessment of the oviduct. Optical coherence tomography is analogous to ultrasound except that it measures the backreflection of infrared light rather than acoustical waves.

Design: The ampulla of a human fallopian tube was imaged in vitro using optical coherence tomography. Images were generated in 2 and 3 dimensions.

Setting: University.

Patient(s): Samples were obtained from women who had undergone hysterectomy for leiomyomatosis.

Intervention(s): None

Main Outcome Measure(s): The ability to perform imaging on a micron scale, which is a level of resolution higher than that of any currently available clinical technology.

Result(s): Two- and three-dimensional data sets of the reflectance of a human fallopian tube were acquired. A volume of $5 \times 5 \times 2.5$ mm (length $\times$ width $\times$ depth) was scanned. The axial resolution was 11 μm, and the lateral resolution at the focus was 20 μm. The data sets showed detailed structures of the fallopian tube.

Conclusion(s): Our ability to obtain micron-scale two- and three-dimensional images of an in vitro oviduct suggests that it may be possible to identify and surgically treat tubal causes of infertility. (Fertil Steril® 1998;70:155–8. ©1998 by American Society for Reproductive Medicine.)

Key Words: Optical coherence tomography, infrared, imaging, fallopian tube, infertility, endometriosis, salpingoscopy, spectroscopy

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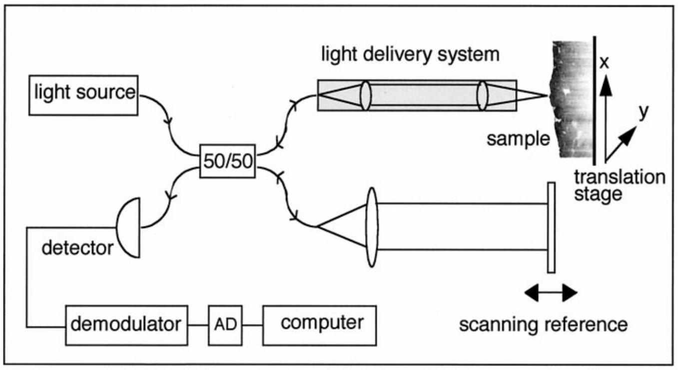
Disorders of the fallopian tubes, such as adhesions, endometriosis, and salpingitis isthmica nodosa, are among the most common causes of infertility. A minimally invasive imaging method, capable of assessing tubal abnormalities at the micron scale, would be a powerful tool both for the diagnosis of these disorders and for the guidance of their surgical repair. In this study, the feasibility of a new micron-scale imaging technology known as optical coherence tomography was evaluated for high-resolution imaging of the oviduct.

Optical coherence tomography is analogous to B-mode ultrasound (US) except that it measures the intensity of backreflected infrared light rather than acoustical waves (1). Optical coherence tomography can perform imaging at 5–15 μm, which is up to 25 times higher resolution than high-frequency US. Optical coherence tomography originally was developed for high-resolution imaging of the transparent tissue of the eye (1). Recent work has led to its use in imaging of nontransparent tissue (2, 3).

In addition to its high level of resolution, there are other reasons to believe that optical coherence tomography will be a powerful tool for assessing the oviduct. First, optical coherence tomography is performed at high speeds. Current systems save to video at acquisition rates of 4–8 frames per second, and systems near video rate are likely to be developed with future modifications (3). Second, optical coherence tomography is based on technology used

FIGURE 1

Schematic of the optical coherence tomography system. Optical coherence tomography is based on an optical interferometer implemented using a low-coherence light source and fiberoptics. The system measures the optical backscattering versus the depth in the tissue. Two- and three-dimensional images are constructed by performing measurements at different transverse positions on the specimen. *AD* = analog to digital converter.



in fiberoptic communications and eventually will allow imaging to be performed through small endoscopes, laparoscopes, or pencil-sized handheld probes (3). Third, unlike US, optical coherence tomography can be performed through air without the need for direct contact or the introduction of a transducing medium (i.e., saline). Finally, the optical coherence tomography system is compact and portable, approximately the size of a desktop computer. In this study,

FIGURE 2

(**A**) An optical coherence tomography image of a human ampulla in vitro. The axial resolution is 11 μm. (**B**) The mucosal folds (m) can be seen clearly and were confirmed by histologic evaluation.

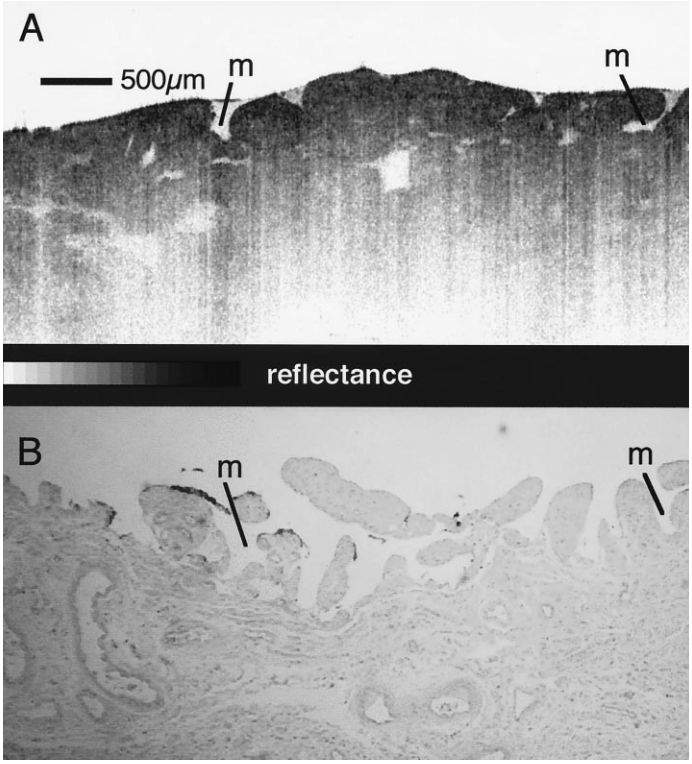
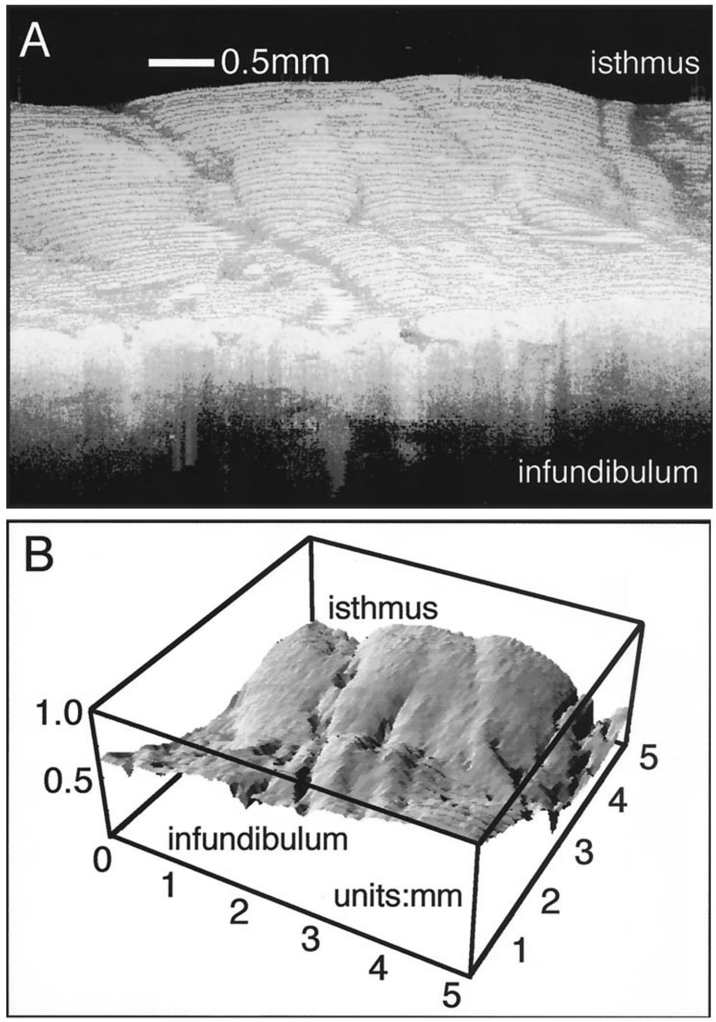


FIGURE 3

(**A**) A three-dimensional optical coherence tomography image of a human ampulla. An area 5 × 5 × 2.5 mm (length × width × depth) was scanned. The number of pixels in the image is 500 × 500 × 50 (length × depth × width). (**B**) A surface plot of the ampulla.



two- and three-dimensional imaging of an in vitro human fallopian tube was performed to demonstrate the feasibility of optical coherence tomography as a new technology capable of assessing this clinically important structure.

MATERIALS AND METHODS

Three fallopian tubes were obtained from women who had undergone hysterectomy for leiomyomatosis. The fallopian tubes were cut open and imaged in an x-y plane, similar to an open surgical field, rather than through the prototype endoscope, which is still relatively large (1 mm). After imaging, the ampulla was processed histologically and registered as previously described to allow correlation with optical coherence tomography images (4). The protocol was approved by the Committee on the Use of Human Subjects at Massachusetts General Hospital.

Figure 1 presents a schematic of the optical coherence tomography system. The principles underlying optical coherence tomography have been described previously (1, 2). Optical coherence tomography measures the intensity of backreflected infrared light in a manner analogous to US. The time that it takes for light to return to the detector, or the echo delay time, is used to measure distances. Because of the high speed of light, this time cannot be measured electronically and a technique known as low-coherence interferometry is used. The axial resolution of the system was measured to be 11 μm, consistent with the theoretically predicted performance (3). The lateral resolution was measured to be

20 μm (3). The acquisition rate was about 40 seconds for one cross-sectional image.

RESULTS

Figure 2A shows an optical coherence tomography image of a human ampulla in vitro. The image consists of 50 $\times$ 500 $\times$ 500 pixels and measures 5 $\times$ 5 $\times$ 2.5 mm (length $\times$ width $\times$ depth). The mucosal folds of the ampulla can be seen clearly. The identity of the tissue was confirmed by histologic evaluation (Fig. 2B). Figure 3A shows a three-dimensional data set of the ampulla. Fifty cross-sections were acquired with a lateral spacing of 100 μm. Note the variation in the structure of the ampulla toward the infundibulum (i.e., the folds become smaller). The imaging penetration was limited to 2.5 mm. Figure 3B shows a surface plot of the ampulla calculated from the acquired optical coherence tomography data. Optical coherence tomography previously has been shown to be well within safety standards, even for the eye.

DISCUSSION

The data in this study demonstrate that optical coherence tomography can define detailed structures of the fallopian tube at resolutions higher than those of any currently available clinical imaging technology. The corresponding histologic evaluation confirmed the tissue identity. Future work will focus on the imaging of pathologic conditions, the development of a small optical coherence tomography endoscope, and the development of inexpensive and clinically viable light sources.

The most exciting potential application of optical coherence tomography remains minimally invasive intraluminal imaging. The development of thin endoscopes, small enough to be introduced into the oviduct, is currently under investigation. It also is important to identify clinically viable light sources for optical coherence tomography. In this study, a short-pulse solid-state laser was used as a broad bandwidth light source, but these instruments are not clinically viable sources because of their relatively high cost and complexity. However, alternate sources with similar wavelength characteristics that are compact and inexpensive are under development.

Our ability to obtain micron-scale images of an in vitro oviduct suggests that it may be possible to identify and surgically treat tubal causes of infertility.

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