Abstract
論文内容の要旨

Title of Dissertation: Development of Vari-focal Liquid Lens with High Numerical Aperture for Endoscopic Applications（内視鏡応用のための高開口数な可変焦点液体レンズの開発）

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Medical endoscopy have played important roles as diagnostic and surgical guide tools, since it allows us to inspect and to treat the inner cavities of the human body in minimally invasive ways. In conventional video endoscopy, objective lens has been designed to have large depth of field (DOF) for avoiding blurry images. On the other hand, in recently proposed advanced endoscopy technologies such as confocal endomicroscopy and three-dimensional (3-D) shape measurement endoscopy, small DOF objective lens is required to achieve high-resolution and 3-D imaging, because the small DOF lens allows to focus locally against the specimen. Numerical aperture (NA) is a value representing the light gathering power of the lens, and small DOF can be acquired by high-NA objective lens, because NA has inverse proportional relationship with DOF. One of the main challenges for conducing advanced endoscopy imaging *in vivo* with high-NA objective lens is maintaining focus within the tissue when patient motion and irregular tissue surface are present. Previously, variable focus optics for endoscopic applications have been demonstrated to change the focus for maintaining the focus within the tissue using actuators such as piezo electric transducer and linear motor. It showed the capability to change the focus, however, this optics still have problems such as large device size, slow focusing and low imaging quality.

One possible solution to solve these problems is to use a vari-focal liquid lens inside the optics of endoscopic device. Vari-focal liquid lens can change the focus rapidly without moving objective lens physically in the optics of endoscopic device. It has potentials for miniaturization, quick focusing and stability for water-immersion interface. Various imaging applications with vari-focal liquid lens have been demonstrated for laparoscopic imaging, endoscopic optical coherence tomography and self-adjustable glasses. However, most of proposed vari-focal liquid lenses have relatively low NA, 0.01 to 0.24, which is not suitable for advanced endoscopy applications such as confocal microscopic imaging and 3-D shape measurement.

In this thesis, the development of a miniature vari-focal liquid lens for endoscopic applications is reported that could hydraulically control the focal length while maintaining high-NA. The high-NA vari-focal liquid lens is composed of a high-NA lens and a vari-focal liquid lens. Most of the optical power is provided by the high-NA lens, and the vari-focal liquid lens changes the optical power to change the focal

length. The optical liquid was contained in a chamber formed by the top surface of the high-NA lens, a lens holder, and a thin Polydimethylsiloxane (PDMS) membrane. The liquid volume of the chamber was changed by a syringe mounted on a translation stage, which changed radius of curvature of the PDMS membrane and subsequently changed the focus.

The miniature vari-focal liquid lens is designed and fabricated with optics of spectrally encoded confocal microscopy (SECM) endoscopic probe. Key parameters of the vari-focal liquid lens are determined through an iterative optimization process using optical simulation software. As the result of optimization process, the PDMS membrane thickness was set as 250 μm, the liquid refractive index was 1.33 (water), and the thickness of the liquid chamber was 1 mm. The vari-focal liquid lens has a diameter of 5 mm and thickness of 4 mm. Then, optical and mechanical performances were tested with SECM endoscopic probe optics. A vari-focal range of 240 μm was achieved while maintaining lateral resolution better than 2.6 μm and axial resolution better than 26 μm. Dynamic response of the vari-focal objective lens was measured to be 11.4±1.3 ms and when the pressure transducing tube of 1.52 m long and 0.86 mm ID was attached to the vari-focal liquid lens, the 10% to 90% response time was measured to be 18.1±0.8 ms. Volumetric SECM images of swine esophageal tissues are obtained over the vari-focal range of 260 μm. SECM images taken by developed lens clearly visualized cellular features of the swine esophagus at all focal depths, including basal cell nuclei, papillae, and lamina propria.