HYDRAULICALLY CONTROLLED MAGNETIC BOUGIENAGE FOR CORRECTION OF LONG-GAP ESOPHAGEAL ATRESIA

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INTRODUCTION
Esophageal atresia (EA) is a rare anatomical defect found in infants, who are born with their esophagus disconnected. EA with a relatively short gap, less than 2cm, can be readily corrected by surgical connection. However, EA with a long gap, 2-7cm, requires treatment over the course of weeks to elongate the esophageal pouch so that it can grow to a sufficient length for surgery. The standard operation for long-gap problem is Foker method [1]. It works for a wide range of EA, but at the expense of several thoracotomies and weeks of continuous anesthesia. To develop minimally invasive correction, several in-lumen methods have been proposed [2, 3, 4, 5]. Such methods insert a bougie into the esophageal pouch to apply stretching force for stimulating it to grow. Our bougie design uses a friction-drive controlled catheter with a tip supplying magnetic force modulated by a hydraulic piston to control the stretching force.

DEVICE DESIGN
The force between two permanent magnets increases exponentially as the gap size decreases. For short-gap EA, where the magnetic force is always bigger than the stretching force of the esophagus, bougienage can be done using only the magnets [6]. For long-gap EA, however, the magnetic force is not always larger than the stretching force, so that it needs to be complemented with mechanical pushing force. In our design, a mechanical pushing force can be applied either by feeding a catheter with the friction drive or by modulating the tip displacement of the bougie hydraulically.

The bougie is designed based on a syringe mechanism, whose plunger is made of ring type permanent magnets as shown in Figure 2. The tip displacement of the bougie can be modulated by injecting water through the central hole of the magnetic plunger. The hydraulic piston applies a pushing force on the esophageal pouch, and it also functions as an active standoff device that pulls the two magnets apart when the magnetic force becomes too large. Two devices are required for bougienage; one for the proximal esophageal pouch and the other one for the distal esophageal pouch. The two bougies can be identical, or the one for the distal pouch can be a simple magnet without a hydraulic mechanism.

The magnetic plunger is connected to a catheter
and the friction drive moves the catheter back and forth to set the neutral gap distance between the two magnets. In other words, the friction drive generates the long-stroke motion for bougienage. A brushless DC motor drives the friction wheel, which feeds the catheter into the esophageal pouch to move the bougie by a commanded displacement. The friction drive is attached to a rigid reference frame to carry reaction force from the catheter. There is a rigid mouthpiece with a curved guiding tube near the friction drive, which provides lateral supporting force for the catheter to avoid buckling.

A syringe pump injects water into the hydraulic bougie through a catheter, so that the tip displacement of the bougie can be modulated to generate short-stroke for bougienage. There is a pressure sensor at the outlet of the syringe pump, which measures hydrostatic pressure in the catheter to estimate the bougienage force, or stretching force of the esophageal pouch. The bougienage force can be regulated around the desired value by modulating the friction drive and the hydraulic bougie. At present, we have conducted bench-level testing of the key components along with control software implemented in LabVIEW running on an NI CompactRIO controller. The stretching force of the esophagus model shown in Figure 3 was measured with the hydraulic bougie. There was a discrepancy between the bougie measurement and the load cell measurement, which is resolved by dithering the hydraulic bougie to compensate the o-ring friction.

FIGURE 2. A hydraulically controlled magnetic bougie. It consists of three ring type NdFeB magnets, two spacers, two o-rings, and a outer bat- ter. A barrel can move with respect to the magnet plunger by injecting water.

REFERENCES