

# Blowfish-Inspired Alternative Magnetic Field Inflation Module for On-Demand Anchoring and Enhanced Visual Detection of Capsule Endoscopes

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Capsule endoscopes are valuable in gastrointestinal diagnostics; however, it has limited effectiveness in the large intestine, as its stability is affected by the colon's large size and continuous muscular activity. Therefore, to enhance capsule endoscopes' anchoring performance in the large intestine, an innovative inflation module is developed to attach to their tail or integrate as a soft shell. The module supports the intestinal wall, stabilizing the device and broadening its field of view while allowing targeted examinations. A detailed characterization analysis of the inflation module is conducted using controlled settings to validate its design. In addition, the module is rigorously tested in simulated environments to assess its core functions; this is followed by in-vitro trials within a large intestine phantom and ex vivo porcine large intestine models. These tests demonstrate the combined module and capsule endoscope's ability to anchor securely, provide a steady field of view, and adapt to the large intestine's unique structure, supporting its application in diagnostic imaging of the gastrointestinal tract. This approach has the potential to enhance capsule endoscopes' diagnostic precision and advance non-invasive gastrointestinal tract observation technology.

capsule endoscopy,<sup>[7,8]</sup> play a vital role in this process. Capsule endoscopy, in particular, offers distinct advantages by addressing blind spots in small intestine observations and eliminating the need for patient sedation.<sup>[9,10]</sup> The procedure allows the capsule to pass naturally through the digestive tract, providing non-invasive visualization. Currently, the capsule endoscopes available are effective for observing the esophagus,<sup>[9]</sup> stomach,<sup>[11]</sup> and small intestine<sup>[12]</sup> but not the large intestine. The large intestine's complex anatomy, specifically the circular muscle structure, poses considerable issues.<sup>[13]</sup> Therefore, traditional capsule endoscopes often incorporate additional cameras to address the problem of maintaining a forward-facing orientation and image stability in the uneven muscular environment of the gastrointestinal tract.<sup>[14,15]</sup> However, the capsule's movement through the colon is

still impeded by the protruding circular muscles, making smooth navigation difficult and limiting the effectiveness of large intestine diagnostics. Therefore, observing the large intestine, especially the colon region, remains a challenge.

## 1. Introduction

Digestive system diseases are becoming increasingly prevalent, making early detection through regular screening crucial.<sup>[1–3]</sup> Diagnostic procedures, such as gastroscopy,<sup>[4]</sup> colonoscopy,<sup>[5,6]</sup> and

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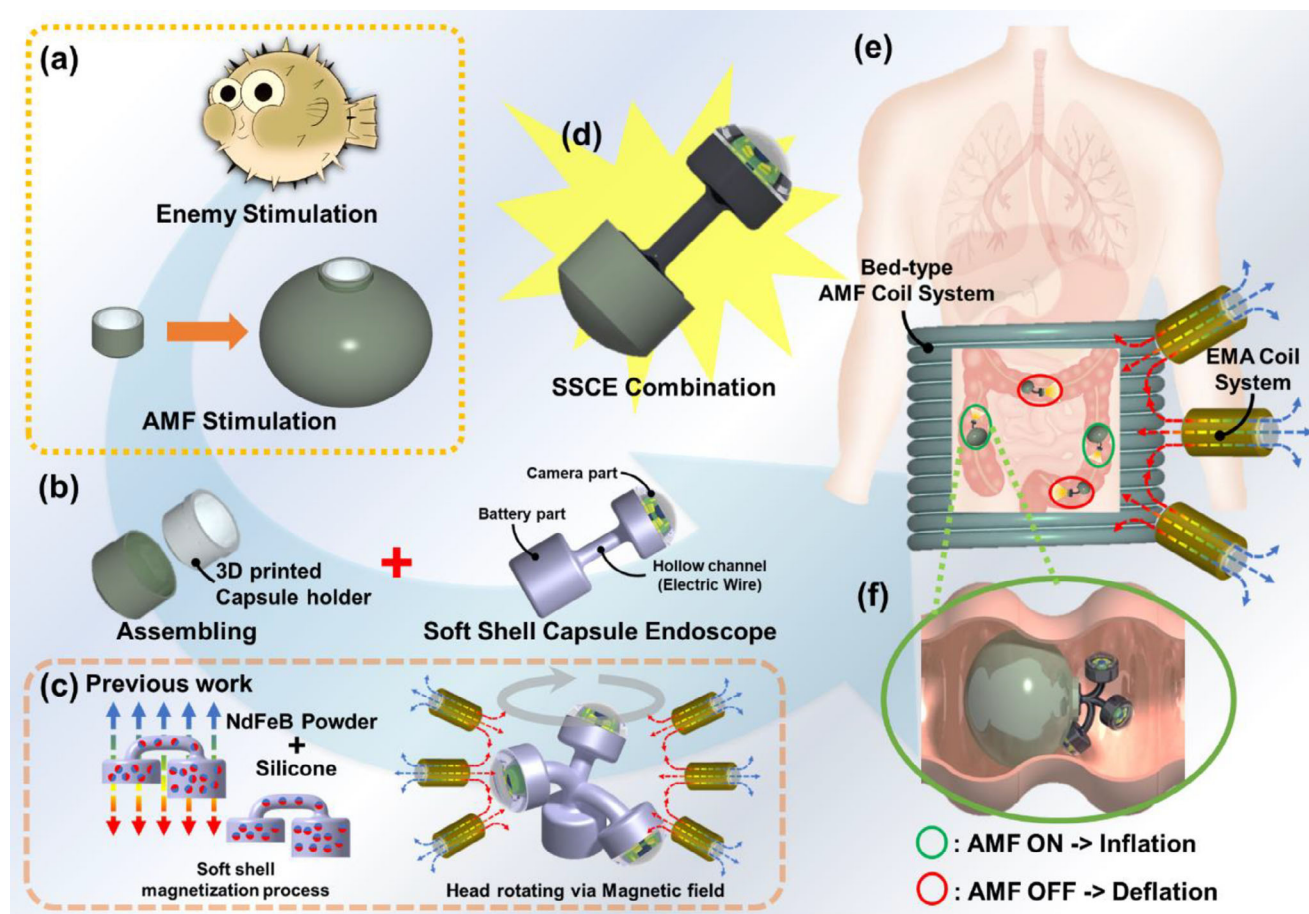
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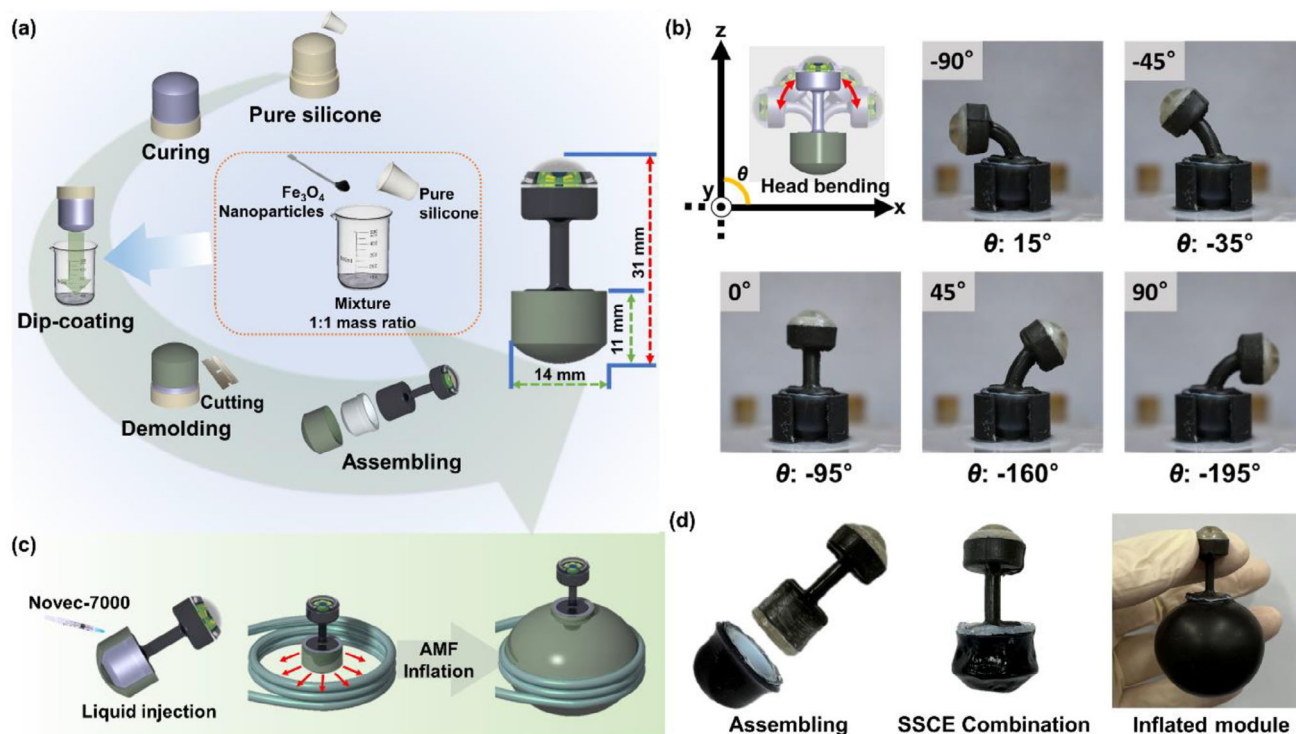
**Figure 1.** Schematic diagram of the inflation module and soft shell capsule endoscope (SSCE) combination. a) An inflated blowfish via enemy stimulation was applicable to develop the inflation module. b) The inflation module was assembled with an outer membrane and a 3D-printed inner capsule holder and combined with the SSCE. c) The soft shell of the SSCE was fabricated using iron neodymium boron alloy (NdFeB) powder and silicone rubber. After the magnetization process, the head of the SSCE can be controlled through external electromagnetic fields. d) The final structure of the SSCE combination. e) Overview of the proposed SSCE combination inflation module in the large intestine. f) The inflated module anchors in the colon, with the SSCE's flexible body maximizing the observation area at that location. AMF, alternating magnetic field; EMA, electromagnetic actuator.

Several researchers have proposed innovative solutions to address this issue (Figure S1, Supporting Information).<sup>[16–21]</sup> Conceptually, these studies employed a mechanism akin to legs to provide capsule endoscopes' support to the inner wall of the large intestine, thereby enhancing their scope of observation. However, such designs have limitations. A common concern is the use of rigid leg materials, which, when combined with the small contact area between the legs and the intestinal wall, can increase the risk of damaging the delicate mucosal lining. This can potentially lead to abrasions or, in more severe cases, perforation of the large intestine, raising significant patient safety concerns. Addressing this concern, Filip et al.<sup>[22,23]</sup> developed self-stabilizing capsules for imaging of the large intestine using a mesh encased in polyglycolic acid, a material that absorbs water and swells. However, this mechanism did not allow the capsules to resize, which is its biggest limitation. Therefore, methods to make the anchor mechanism more efficient are required.

To address the anchoring instability resulting from the large luminal space and peristaltic forces in the colon, we drew inspiration from biological organisms such as blowfish that temporarily

expand their body volume to resist displacement. Based on this principle, we developed a magnetically inducible inflation module that enables reversible anchoring of capsule endoscopes on demand. We used alternating magnetic field (AMF) stimulation to inflate the module<sup>[24]</sup> (Figure 1a) by optimizing and customizing its design. The design allowed the internal capsule holder to be installed or combined with any commercial capsule endoscope to improve its observation efficiency in the large intestine (Figure 1b). Moreover, this inflation module wirelessly expands through an external AMF, offering numerous advantages. Tang et al.<sup>[25]</sup> were the first to propose the use of similar wireless-controlled inflation in the medical field, pioneering this area of research. Furthermore, the design of the inflation module in this study was inspired by our previous work.<sup>[26]</sup>

Magnetic composites have enabled remote actuation systems with enhanced multifunctionality. Embedding Fe<sub>3</sub>O<sub>4</sub> or other magnetic fillers (e.g., carbonyl iron, ferrites) into thermoplastic matrices such as polyethylene terephthalate glycol<sup>[27]</sup> or thermoplastic polyurethane<sup>[28]</sup> has improved thermomechanical behavior.<sup>[29]</sup> This advancement has enabled shape memory



**Figure 2.** Fabrication and inflation mechanism of the inflation module. a) Fabrication process of the inflation module. b) The soft shell colon capsule endoscope (SSCE) combination head bending via external magnetic actuation control. c) The module's inflation mechanism. d) Images of the SSCE and inflation module combination and the inflated module. AMF, alternating magnetic field;  $\text{Fe}_2\text{O}_4$ , iron oxide; Novec-7000, 3M Novec 7000 engineered fluid.

effects<sup>[30]</sup> and magnetic torque-driven deformation.<sup>[31]</sup> These developments support the growing use of soft, controllable magnetic systems in biomedical and robotic applications.

To this end, the soft shell capsule endoscope (SSCE) was fabricated using iron neodymium boron alloy powder and silicone rubber. After the magnetization process, the SSCE's motion can be remotely controlled by exerting an electromagnetic actuation system (Figure 1c). In addition, we demonstrated the SSCE's advantages in terms of mobility and stomach and small intestine observations. Moreover, the capsule can be moved under the control of natural peristalsis of the stomach or through an external electromagnetic field. The final structure of the SSCE and inflation module combination is shown in Figure 1d. Our vision of clinical feasibility is shown in Figure 1e. The AMF system controls the module's expansion and contraction, and the electromagnetic actuation (EMA) system controls the movement of the capsule head to expand the observation range (Figure 1f). We assessed the performance of this inflation module and capsule endoscope system through in vitro and in vivo experiments.

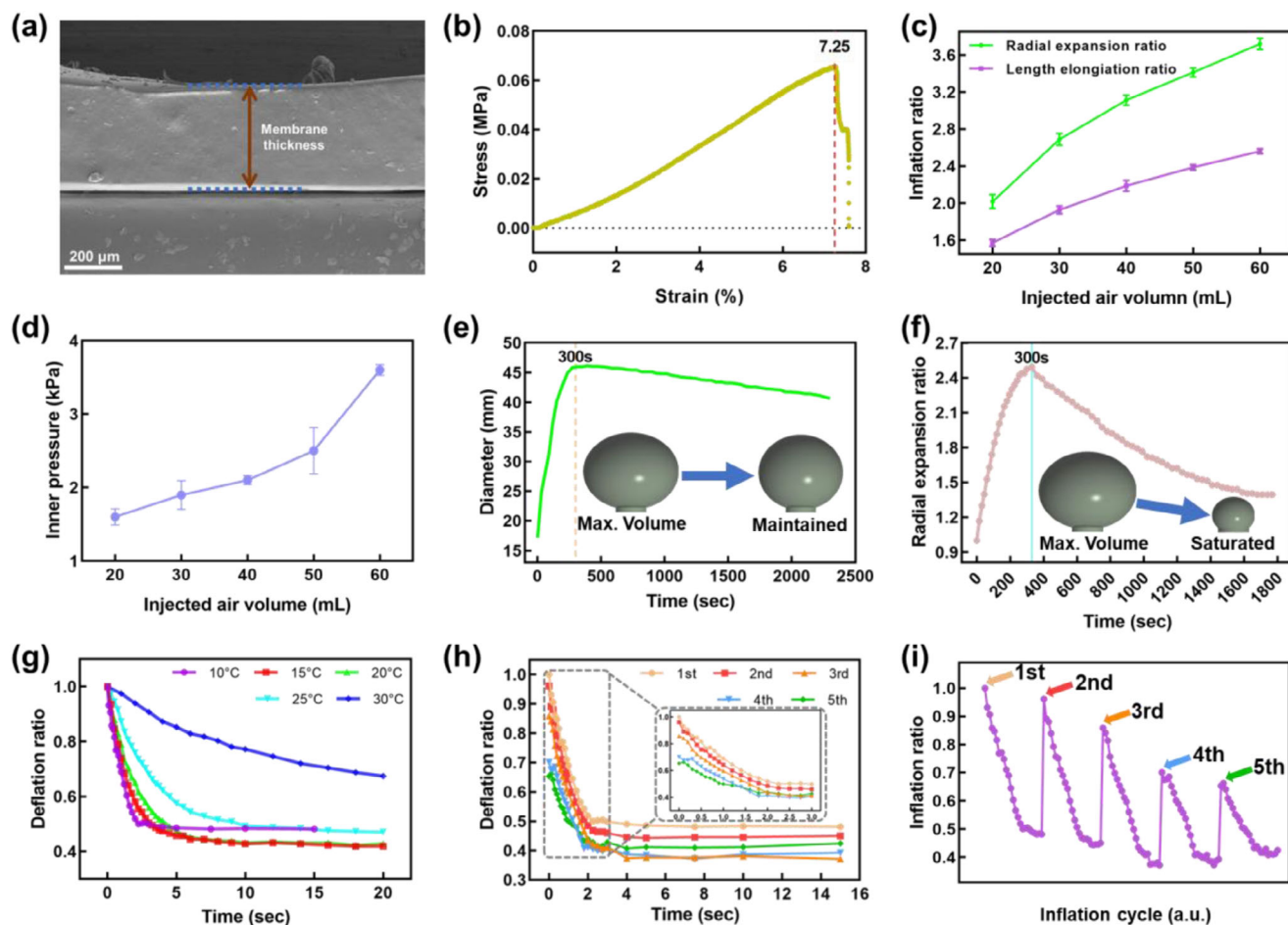
## 2. Results and Discussions

### 2.1. Inflation Module Design and Inflation Mechanism

The inflation module of the capsule endoscope consists of two parts: a 3D-printed inner rigid capsule holder and an outer inflatable membrane. Figure 2a illustrates the fabrication and in-

stallation process of the inflation module, along with a schematic diagram of the inflation mechanism. The outer membrane consists of two layers: pure silicone without any additives and a composite layer mixed with iron oxide powder in a 1:1 mass ratio. Due to the manual mixing of iron powder and silicone, achieving perfect uniformity was challenging, as iron powder particles tend to aggregate. Therefore, an additional layer of pure silicone was applied to reduce the risk of rupture during inflation caused by uneven iron powder distribution. First, pure silicone was evenly poured into a custom cylindrical mold; then, the entire cylinder was coated with the composite mixture using a dip-coating method. Once fully cured, the membrane was cut along pre-designed lines on the cylinder using a blade. A crucial step in the final process was inverting the membrane during demolding to position the pure silicone layer on the capsule endoscope's outer surface, ensuring enhanced protection. The inner holder, crucial for securing the capsule endoscope, was tailored to fit the specific capsule model. Subsequently, the inflation module's capability to anchor securely and facilitate multi-angle observations post-anchoring was verified.

After assembling, the combination was placed in an electromagnetic system, and head-bending experiments were conducted. Figure 2b shows that the head of the assembly was induced to oscillate by adjusting the input value of the electromagnetic field's theta ( $\theta$ ) angle. This experiment validated the stagnation of the SSCE's head at angles of  $-90^\circ$ ,  $-45^\circ$ ,  $0^\circ$ ,  $45^\circ$ , and  $90^\circ$ ; the strength of the magnetic field was 20 milliTesla (mT). The experiment's complete process is presented in Movie S1



**Figure 3.** Characterization and inflation behavior of the module in a human-like environment. a) Thickness measurement of the outer membrane of the inflation module. b) Stress–strain curves, demonstrating the module’s mechanical behavior. c) Correlation between the injected air volume and the module’s inflation ratio in radial and length directions. d) The relationship between the injected air volume and inner pressure. e) Schematic illustration showing the module’s transition from its initial shape to maximum volume, inflation maintenance, and the corresponding diameter change curve. f) Schematic of the module’s inflation process at 40 °C, recovery at 36.5 °C, and the radial change curve. g) Schematic of the module’s inflation at 40 °C, recovery at 10 °C, and the deflation ratio curve at different temperatures. h) Schematic of repeated inflation cycles of the module and the deflation ratio curve for each cycle. i) Maximum radial measurement of the module during each full inflation.

(Supporting Information). Then, low-boiling liquid (3M Novec 7000 engineered fluid; 3 M Company, Saint Paul, MN, USA) was injected into the gap between the holder and membrane using a syringe (Figure 2c). Novec 7000 fluid is colorless, odorless, and has low toxicity; therefore, it was selected as an ideal thermal inflation agent.<sup>[32,33]</sup> The module’s inflation mechanism involved using an AMF, an advanced process that uses radiofrequency wave energy to heat materials, to heat the module and stimulate the evaporation of the injected internal liquid. The mechanism of heating involves the interaction between an AMF and a specific material;<sup>[34,35]</sup> therefore, when the inflation module was exposed to a high external AMF, the iron oxide ( $\text{Fe}_3\text{O}_4$ ) nanopowder within its outer membrane heated up rapidly. This heat caused the internal liquid to evaporate, leading to the rapid inflation of the module’s external membrane, thereby anchoring it within the large intestine. Figure 2d demonstrates the inflation module and SSCE combination.

## 2.2. Characterization of the Inflation Module

The thickness of the inflation module’s outer membrane was measured using scanning electron microscopy. Figure 3a shows that the membrane thickness was  $\approx 420 \mu\text{m}$ ; its typical stress–strain curves are presented in Figure 3b. The strain increased to 720% then decreased and broke, with the stress reaching 0.066 MPa. The elongation of more than seven times allowed sufficient inflation of the module under external stimulation.

In the preliminary analysis of the inflation module’s operational capacity, a comprehensive characterization of its inflation data was conducted. It was essential to first understand the module’s behavior, including inflation ratio and maintaining capability, using a conventional inflation method before transitioning to the external untethered AMF inflation technique. Therefore, a syringe needle was used to inject air into the inflation module to analyze and meticulously record the module’s response to varying air volumes. Figure 3c shows the module’s dimensional changes

during inflation. The results provided insights into the module's length and radial dimension changes with different air injection volumes. Observations indicated that the length elongation rate and the radius increase rate were proportional to the injected air volume. However, a comparative analysis of the two rates revealed a slight disparity. The radial dimension expansion had a higher rate of 3.72 times, whereas the length dimension elongated by only 2.56 times. This subtle difference in the elongation rates of the two dimensions is noteworthy and suggests that the module's materials or design is predisposed to expand more radially than longitudinally, thus assisting in shortening the module's anchoring time. In addition, the internal pressure increased with the amount of gas injected; the internal pressure was 3.6 kPa when the maximum injection volume was 60 mL (Figure 3d).

### 2.3. Inflation Module's Inflation Properties in a Human Body Environment

Inflation maintenance tests were conducted on the inflation module. Ideally, the inflation duration should exceed 1 min to allow sufficient observation at the anchor point. The results revealed that the module took 300 s to fully inflate from its initial state in a 40 °C water environment (Figure 3e; Movie S2, Supporting Information). Furthermore, Figure 3e shows the changes in the module's external diameter with time after reaching its peak diameter value. After full inflation, the module's outer diameter was monitored; by 35 min, the deflation rate was  $\approx 10\%$  of its peak value. The inflation maintenance results supported that the capsule endoscope had enough observation time at the anchor point.

Furthermore, the module's deflation behavior was examined at its maximum inflated size at an external temperature of 40 °C through to cooling to the average human body temperature of 36.5 °C (Movie S3, Supporting Information). Figure 3f shows the module's inflation changes from full inflation at 40 °C, to rapid immersion in warm water at 36.5 °C, and after 24 min. The module began to deflate at 300 s and completed its deflation in  $\approx 25$  min. The results indicated that, when the external stimuli for module inflation were deactivated, it first maintained inflation and then slowly deflated in an environment mimicking humans' body temperature; this eliminated the need for a deflation stimulus, thereby reducing potential medical risks.

After completing point observations in the large intestine, the module's deflation was examined in water at different temperatures to determine the shortest deflation time after full inflation. Figure 3g shows the temperature range between 10 °C and 30 °C in 5 °C increments. The module's deflation was slowest at 30 °C, taking about 1 min, and fastest at 10 °C, taking  $\approx 2$  s. Theoretically, there is no clear standard for module deflation time. However, to get to the next anchor point for observation as quickly as possible, the deflation time should be as short as possible. The results showed that when the external temperature was as low as possible below the boiling point, the phase change from gas to liquid was accelerated.

In addition, repeated inflation and deflation tests were conducted in an efficient deflation environment at 10 °C (Figure 3h) because this temperature showed the shortest deflation time in this environment. In clinical applications, the module needs to

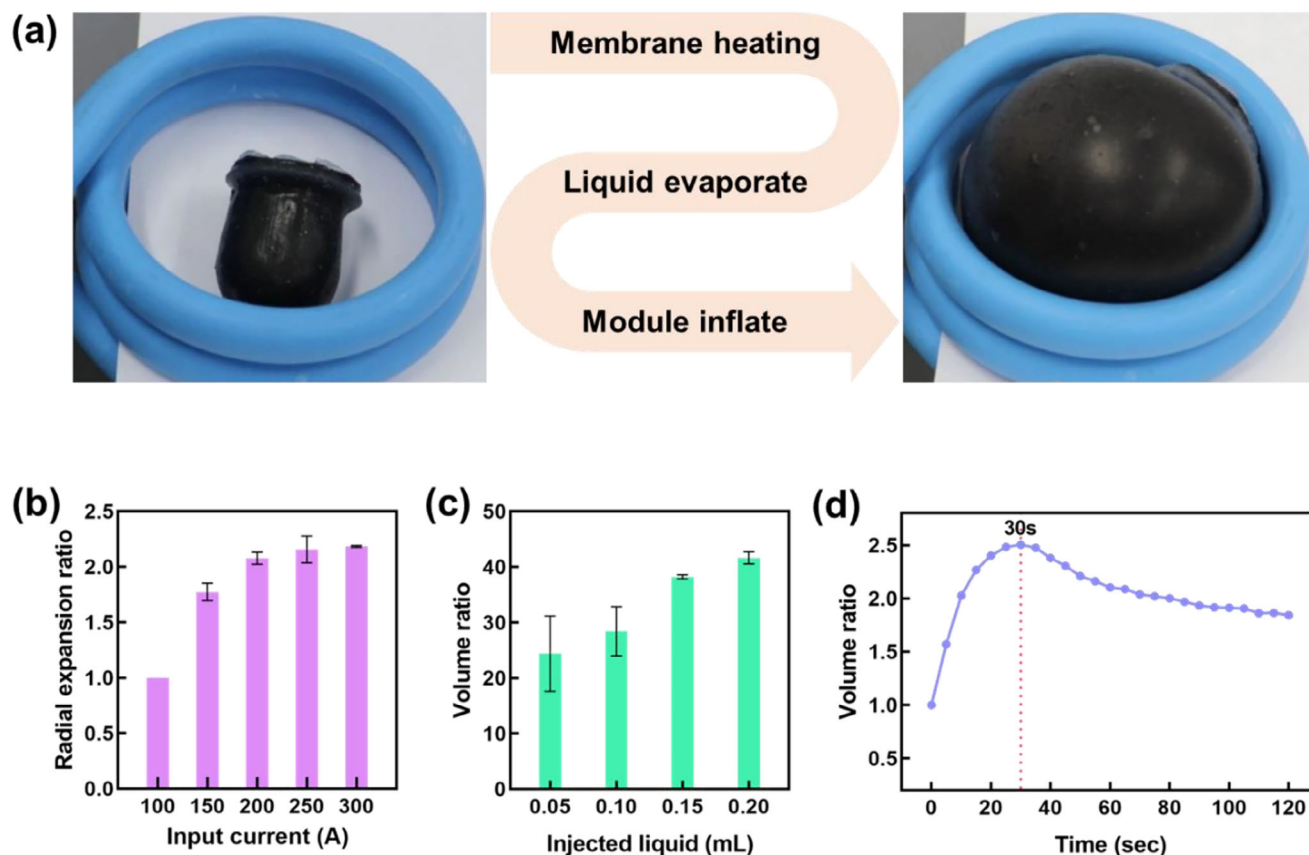
be inflated multiple times within a limited period to maximize the number of areas observed within the large intestine. It was found that the module could be inflated for three cycles to a size that could be anchored in the large intestine (Figure 3i), which indicates good mechanical repeatability and minimal material fatigue under repeated actuation. This consistency suggests that the module is capable of supporting multiple anchoring events during a single diagnostic session without significant performance degradation.

The insufficient inflation observed from the fourth cycle onward was primarily caused by the gradual loss of the low-boiling-point liquid during repeated phase transitions, which resulted in an inadequate amount of fluid to fully inflate the module. Mechanical fatigue of the membrane, however, was not the limiting factor within our tested range. As shown in Figure S3 (Supporting Information), we subjected the membrane to nearly 70 cycles of stretching and relaxation to simulate the inflation and deflation process. The stretching was set to approximately threefold elongation, comparable to the maximum radial expansion achieved under AMF stimulation, reaching this state in  $\approx 30$  s, maintained for 120 s to simulate anchoring, and then returning to the initial size within  $\approx 3$  seconds. The results indicated that the membrane began to reach a saturation state after  $\approx 20$  cycles, but no obvious decline in mechanical performance was observed throughout the entire test.

### 2.4. Using an Alternating Magnetic Field to Stimulate Inflation

Figure 4a and Movie S4 (Supporting Information) show the module's inflation process when it is exposed to an AMF. An AMF was strategically applied to act on the magnetic particles embedded within the outer membrane of the inflation module. These embedded particles experience a rapid increase in temperature, heating a low-temperature evaporative liquid contained within the module; this liquid undergoes a phase change to vapor, resulting in the inflation of the module. Through this vaporization-driven inflation, the module effectively supports the inner wall of the large intestine, enhancing the capsule's stability and observational range.

To investigate the relationship between the AMF input current and the module's radial expansion rate, experiments were conducted using input currents ranging from 100 to 300 A in 50 A increments. The input frequency was fixed at 272 kHz, and the internal solution volume was maintained at 0.1 mL. No inflation response was observed at 100 A. As the current increased, the expansion rate also increased, with the highest radial expansion ratio of 2.19 recorded at 300 A (Figure 4b). At this level, the inflation behavior was highly consistent across repeated trials. When the amount of injected solution was varied while holding the current at 300 A, the volume inflation rate increase corresponded with the solution volume. Notably, the inflation rate rose to 41 when the internal solution was increased to 0.2 mL (Figure 4c). No inflation occurred when the solution volume was below 0.05 mL; however, volumes exceeding 0.2 mL prevented complete deflation, suggesting that excessive liquid can prompt premature inflation. The variability observed at the injected volume of 0.05 mL in repeated experiments is primarily due to the insufficient amount of thermal agent, which often results in incomplete vaporization



**Figure 4.** Characterization of the inflation module through alternating magnetic field (AMF) stimulation. a) The three stages of the inflation module's shape transformation under AMF stimulation, from its initial to fully inflated form. b) Correlation between the input current of the AMF system and the module's radial expansion ratio. c) Relationship between the injected liquid volume and the module's volume change ratio. d) Performance curve of the inflation module during AMF power ON and OFF. A, ampere.

and inconsistent inflation under AMF stimulation. In contrast, injected volumes of 0.15 mL or greater fall within the optimal range for uniform heating and complete phase transition, leading to a more stable and reproducible inflation profile.

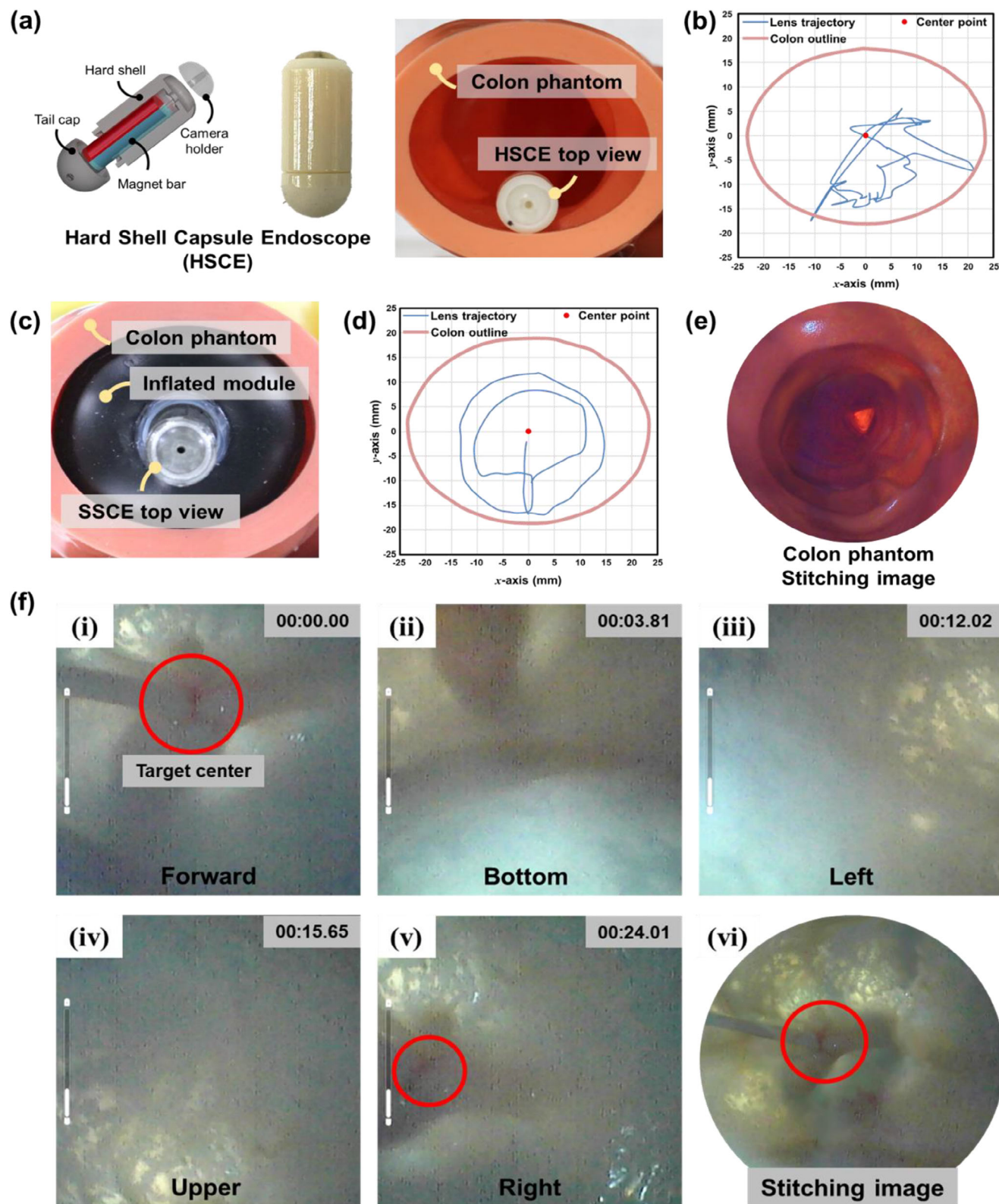
Following the initial assessment, the system's peak capacity was used to maximize efficiency, that is, inputting 300 A for the coil current. Hypothetically, a higher input current amplifies the stimulation of the soft magnetic powders, subsequently enhancing the module's inflation efficiency. Figure 4d demonstrated that the inflation reached saturation at  $\approx 30$  s, showing the maximum radial value. The module deflated after turning off the power and reached another saturation point at 120 s. However, the module did not revert to its original shape after deactivating the external stimulus; this was attributed to silicone's properties, as when it is expanded beyond its strain limit, it undergoes permanent deformation, hindering its ability to return to its initial form.

A critical consideration in applying the AMF stimulation method is human adaptability, particularly given the rapid temperature increase associated with this approach. Although this temperature rise is inherent to AMF stimulation, it poses a challenge in achieving precise, continuous control of body temperature at the exposed site. Hao et al.<sup>[36]</sup> addressed this concern by utilizing ultrasonic stimulation to trigger a phase change in the internal solution of a soft robot to induce inflation, thereby sim-

ulating drug release and controlling multi-channel point release. Their findings indicated that the tissue damage due to the temperature rise during inflation was negligible, suggesting a minimal impact on the tissue surface from the inflation mechanism's heat (Figure S4, Supporting Information).

## 2.5. In Vitro Colon Phantom Scanning Experiment

A comparative study was conducted between a hard shell capsule endoscope (HSCE) and an inflation module-assembled SSCE to verify the advantages of combining the module's anchoring stability. The construction of the HSCE is shown in Figure 5a; it comprises a 30 mm-long and 10 mm outer diameter shell made using a 3D printer. A permanent cylindrical magnet is incorporated into the shell, which is capable of responding and being controlled by externally applied electromagnetic fields. The HSCE was placed inside a colon model, and internal scanning was performed under the control of an external 10 mT AMF. The inner wall of the colon model is outlined by the pink ellipse, the red dot marks the relative center point, and the blue solid line represents the optimized camera movement trajectory (Figure 5a). By tracking the displacement of the capsule endoscope's frontmost section (the lens position), irregular and



**Figure 5.** In vitro and ex vivo experiment results. a) Composition of the hard shell capsule endoscope (HSCE) and the experiment setup in a colon phantom. b) Trajectory path of the HSCE's camera. c) Inflation module and soft shell capsule endoscope (SSCE) combination experimental setup in a colon phantom. d) Trajectory path of the SSCE's camera. e) Stitched image of the colon phantom. f) Ex vivo test of the SSCE combination conducted in a porcine large intestine: i) The red circle indicates the forward direction and the central point of the test; ii–v) Scanning sequence in the order bottom, left, top, and right; vi) Final stitched image obtained from the scan.

dynamically uncontrollable movements were observed (Figure 5b; Movie S5, Supporting Information). Additionally, from the perspective of observing the HSCE in the colon model's inner surface, it was evident that the rotational issues of the lens itself negatively impacted the observations (Movie S6, Supporting Information). These experimental results align closely with the problems this study aimed to address.

Subsequently, the SSCE combined with the inflation module was placed at the same location as used for the HSCE experiment, and multi-range scanning was conducted at a single point to evaluate its stable imaging performance. Once in place, air was injected to inflate the module fully, securing it against the inner wall of the colon (Figure 5c). A 10 mT external AMF was then applied to rotate the suspended SSCE head around a central axis (Movie S7, Supporting Information). The resulting images were analyzed frame by frame to track the SSCE camera's movement path. Figure 5d shows that the SSCE's trajectory closely approximated a perfect circle, confirming that the scanning was stable and continuous following anchoring. This achievement aligned well with the study's primary goal of minimizing camera jitter to improve image stability (Figure S2, Supporting information).

Additionally, a post-analysis was conducted by stitching the recorded images to create a panoramic view from single-point imaging (Figure 5e). The SSCE was inverted, and the scanning process was recorded from a first-person perspective (Movie S8, Supporting Information). While this image was produced through post-processing, developing real-time stitching capabilities for panoramic imaging was an intended goal for future research related to this study. Single-point and multi-point panoramic imaging can increase the efficiency of intestinal examinations and provide medical professionals with a comprehensive view of the patient's condition, enhancing diagnostic accuracy and patient care.

## 2.6. Ex Vivo Assessment of Capsule Passability and Scanning in Porcine Intestine

To further assess the applicability and functionality of the inflation module in practical scenarios, ex vivo experiments were conducted using a porcine colon. We first performed passability experiments in porcine small and large intestines (Movie S9, Supporting Information). The results confirmed that the capsule with the integrated inflation module was able to traverse smoothly in its deflated state, demonstrating good active passability in both models. Air was injected into the module after assembling it onto the SSCE, and the assembly was inserted into the large intestine; this provided the SSCE with full support to the intestinal walls. A multi-range observation was then conducted within the large intestine using an AMF set to an external strength of 10 mT (Movie S10, Supporting Information), as illustrated in Figure 5f. Figure 5f (i) displays the initial image captured at the start of the experiment; the red circle marks the front end of the large intestine, enabling orientation confirmation for subsequent observations. Figure 5f (ii–v) shows screenshots captured from the bottom, left, upper, and right sections during the rotational scan, demonstrating that a comprehensive scan was achieved for the observable area at this position. Moreover, Figure 5f (vi) presents a stitched panoramic image of the

large intestine's interior, created through post-processing after the scan. This stitched image illustrates the potential to generate a complete, detailed view, supporting the inflation module's suitability for broad and effective observation within the large intestine.

## 3. Conclusion

In this study, we developed an inflation module designed to integrate with capsule endoscopes to enable stable observation within the large intestine. This inflation module provided the capsule endoscope support to the inner walls of the large intestine, allowing for stabilized movement and consistent observations. To further expand the observation area during anchoring, we explored a structure comprising an SSCE incorporating the inflation module. This module, which features customizable internal components, utilizes an AMF heating method for inflation. The AMF interacts with the soft magnetic powder embedded in the module's outer membrane, generating heat that vaporizes a low-boiling-point liquid inside the module. This vaporization inflates the module, effectively anchoring the capsule against the inner wall of the large intestine. For extensive validation, we conducted experiments using a human large intestine phantom and ex vivo porcine large intestine models. These experiments provided valuable insights into the module's performance and its ability to support endoscopic procedures.

While inflation requires several minutes under AMF heating and deflation occurs passively at body temperature, the module successfully achieved anchoring and multidirectional scanning in physiologically relevant environments. Thermal characterization across a wide temperature range confirmed the reliability of the phase change mechanism and offered key data for modeling inflation dynamics.

Importantly, this foundational characterization supports the future integration of closed-loop control, in which embedded sensors such as, pressure detectors, or temperature detectors can provide real-time feedback on lumen geometry, wall contact, or image quality. Such feedback would enable autonomous modulation of inflation and deflation, enhancing stability, safety, and diagnostic precision in dynamic gastrointestinal conditions.

In future work, temperature control strategies using alternative approaches such as Peltier-based modules may be considered to complement the AMF-driven system. Although this concept was not experimentally validated in the present study, it could potentially improve responsiveness and enable closed-loop control in clinical applications.

## 4. Experimental Section

**Materials:** The capsule's flexible exterior was fashioned from silicone rubber, specifically Ecoflex 00-20 (Smooth-On, Inc., Macungie, PA, USA). The Sigma-Aldrich iron oxide ( $\text{Fe}_3\text{O}_4$ ) nanopowder with a particle size between 50 and 100 nm was sourced from Merck KGaA, Darmstadt, Germany, and the 3 M Novec 7000 engineered liquid was from the 3 M Company, Saint Paul, MN, USA. The human phantom haustrum was purchased from the ASAN Medical Center, Seoul, South Korea.

**Fabrication of the Inflation Module:** A capsule-shaped 3D mold was employed to create the module's outer inflatable membrane. This mold underwent a surface treatment according to Section 2.1. The process began by applying pure silicone to the treated mold. Once set, a mixture

of magnetic nanoparticles and silicone rubber was added using the dip-coating technique. A cutting tool was used to carefully detach the outer membrane from the mold. Ensuring the position of the mixture layer internally was essential to allow the pure silicone layer to protect the module during inflation. To guarantee an airtight seal, Sil-Poxy (Smooth-On, Inc.) was used to bond the opening of the outer membrane to the protruding section of the module's inner holder.

The design of this custom module was tailored to the SSCE's tail dimensions, which were 10 mm in length and a radius of 6 mm. The inner holder measured 9.6 mm, with inner and outer diameters of 12 and 13 mm, respectively; the thickened part at the upper end was 14 mm. The mold was in the form of a cylinder measuring 14 and 8 mm in diameter and length, respectively. The curved design at the mold's apex was crafted to mimic the tail end of the capsule endoscope.

**Characterization of the Inflation Module:** The thickness of the outer membrane was examined using a scanning electron microscope (SU8010, Hitachi High-Tech Corp., Tokyo, Japan) and ImageJ software (National Institutes of Health, Bethesda, MD, USA).

**Electromagnetic Actuation System:** The EMA system consisted of one pair each of Maxwell, Helmholtz, and rectangular coils, and was capable of generating magnetic fields up to 35 mT. This setup enabled a full five degrees of freedom (DOF) motion, with 3-DOF translation and 2-DOF rotation. The system's magnetic workspace measured 60 × 60 × 60 mm at the center of the coil configuration. Control of the EMA system was achieved through eight power supplies, including four NX15 and four 3001iX units (AMETEK, Inc., Berwyn, PA, USA), all operated via a LabVIEW program (National Instruments Corp., Austin, TX, USA).

**Ex Vivo Validation:** Fresh porcine large intestines were sourced from Samho Butcher Shop in Buk-gu, Gwangju, South Korea (geographic coordinates: 35.19424°N, 126.87898°E).

**Stitching Images:** Python's OpenCV library (Python Software Foundation, Wilmington, DE, USA) was used to extract frames from the colon capsule endoscopy and pig colon endoscopy videos to prepare for image stitching and analysis. For the colon capsule endoscopy phantom (6546 images), segments with screen jitter were removed at the beginning and end of the video. In addition, the left-side scrollbar visible in the original video was cropped. Similarly, the left scrollbar was cropped from 1398 pig colon endoscopy images.

To perform the image overlapping feature point stitching, ibisPaint X freeware (Ibis Inc., Nagoya, Aichi, Japan) was used. For the colon capsule endoscopy phantom, overlapping feature points were identified using the haustral folds within the colon as a primary feature point; a bright orange triangular shape was aligned with the image end as a secondary point. For synthesis, a set of 30 clear images taken from multiple directions (bottom, left, upper, and right) was selected based on minimal blur and clear structure. For accurate alignment in stitching, the central black line in the images was used as the main feature point in the porcine large intestine, and the bumpy surrounding inner lining was used as a secondary point.

## Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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## Conflict of Interest

The authors declare no conflict of interest.

## Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

## Keywords

alternative magnetic field, capsule endoscope, inflation module, on-demand anchoring

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