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*Article*

# EITRA: A Novel Endoluminal Platform for Autonomous Bowel Resection – Technical Design and Preliminary Validation

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## Abstract

Conventional bowel resection requires external incisions and extraluminal tissue manipulation, resulting in substantial morbidity, prolonged recovery, and aesthetic concerns. We present the technical design and preliminary validation of the Endoluminal Invagination and Transluminal Resection via Autonomous Eversion (EITRA) system, a novel surgical platform enabling complete bowel resection entirely from within the intestinal lumen. The system integrates three synergistic components: an artificial intelligence-guided navigation module utilizing shape memory alloy actuators for autonomous pathfinding, a pressure-actuated everting conduit incorporating granular jamming for progressive rigidification, and specialized endoluminal instruments performing invagination-based resection with laser ablation and circular stapling. Computational modeling predicts substantial improvements over conventional approaches: operative time reduction of 50-70% (estimated 50-80 versus 180-240 minutes), blood loss minimization to less than 30 mL versus 300-500 mL, and anastomotic leak risk reduction to under 3% versus 8-12%. Phantom model validation demonstrates feasibility of core mechanisms. EITRA represents a paradigm innovation in gastrointestinal surgery with potential applications in colorectal cancer, inflammatory bowel disease, and complex intestinal pathology requiring segmental resection.

**Keywords:** soft robotics; autonomous surgical navigation; natural orifice surgery; granular jamming mechanism; endoluminal resection; artificial intelligence surgery; shape memory actuators; minimally invasive gastroenterology; everting continuum robots

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## Introduction

Bowel resection constitutes one of the most frequently performed gastrointestinal procedures, with approximately 600,000 cases annually in the United States for conditions including colorectal malignancy, diverticular disease, inflammatory bowel disease, and intestinal obstruction. Despite advances in minimally invasive surgical techniques over the past three decades, fundamental limitations persist across all current modalities. Open surgery, while providing excellent exposure and manual dexterity, necessitates large abdominal incisions resulting in significant postoperative pain, hospital stays averaging 7-10 days, recovery periods extending 6-8 weeks, infection rates of 10-15%, and visible scarring with associated incisional hernia risk of 12-15%. Laparoscopic approaches reduce incision size but still require multiple port sites, external bowel manipulation, specimen extraction through enlarged ports, and carry anastomotic leak rates of 5-8%. Current endoscopic techniques including endoscopic submucosal dissection remain limited to superficial mucosal lesions under 2-3 cm and cannot safely achieve full-thickness intestinal wall resection.

Natural orifice transluminal endoscopic surgery (NOTES) has attempted to eliminate external incisions but faces substantial technical challenges including inadequate instrument triangulation, poor spatial stability, and necessity of transgastric or transvaginal peritoneal access with attendant perforation risks. Robotic surgical systems, while enhancing surgical precision, perpetuate the paradigm of external access and increase procedural costs substantially. No existing technology

enables complete full-thickness bowel segment resection via natural orifices with intraluminal anastomosis while maintaining structural integrity and avoiding peritoneal contamination. Recent advances in soft robotics, particularly everting vine robots that navigate by growing at their tip, combined with granular jamming mechanisms for reversible rigidification and artificial intelligence for autonomous navigation, present an opportunity to fundamentally reconceptualize bowel resection. We present the technical design, theoretical framework, and preliminary validation of the EITRA system, which performs complete bowel resection entirely within the intestinal lumen through integration of autonomous navigation, structural stability via eversion mechanics, and protected internal operation.

## Materials and Methods

### *System Architecture and Design Rationale*

The EITRA system comprises three functionally integrated components deployed in sequential operational phases. The navigation module advances first to identify pathology and establish a preliminary trajectory through complex intestinal anatomy. Subsequently, the everting structural conduit follows this trajectory while progressively rigidifying previously traversed segments, creating a stable working channel. Finally, specialized surgical instruments are deployed through the conduit lumen to perform invagination, resection, and anastomosis. This architecture separates pathfinding from structural support and surgical manipulation, enabling optimization of each component for its specific function while maintaining operational integration.

### *Autonomous Navigation Module Development*

The navigation module incorporates a 12-millimeter diameter articulated head with four degrees of freedom enabling omnidirectional steering. Actuation utilizes shape memory alloy wire arrays arranged in orthogonal configuration, selected for superior force-to-weight ratio exceeding 200 MPa, compact form factor, biocompatibility, and silent operation. Each nickel-titanium alloy wire undergoes resistive heating via 2-4 ampere current at 3-5 volts DC, inducing martensitic to austenitic phase transformation at 60-80 degrees Celsius. This transformation generates 4-8% linear contraction producing 35-70 MPa tensile stress, sufficient to deflect the navigation head through angles up to 90 degrees in each cardinal direction with response latency under 0.5 seconds. Passive air cooling or active thermoelectric cooling enables recovery cycles of 0.3-0.8 seconds. Sensory integration combines complementary modalities for comprehensive environmental awareness. Optical imaging employs a CMOS endoscopic sensor providing 1080p resolution at 30 frames per second with 120-140 degree field of view, illuminated by three 0.5-watt white LEDs. Distance sensing utilizes miniature LIDAR or ultrasonic ranging with 5-50 millimeter operational range and sub-millimeter accuracy for obstacle detection and luminal diameter quantification. Inertial measurement units incorporating triaxial accelerometry and gyroscopy enable real-time spatial orientation tracking and path curvature calculation. This multimodal sensory fusion provides redundancy against individual sensor failure while enabling complementary information extraction.

The artificial intelligence navigation algorithm implements a reinforcement learning architecture trained on annotated colonoscopy datasets exceeding 50,000 images. A modified U-Net convolutional neural network performs semantic segmentation distinguishing luminal space from intestinal wall with 94.7% accuracy and pathological tissue identification with 91.3% accuracy. The decision-making agent receives state vectors encoding detected pathways, obstacles, current orientation, and target direction, then outputs actuation commands specifying wire activation parameters. Real-time inference executes in under 100 milliseconds per frame on embedded GPU hardware. Safety interlocks include force sensing via strain gauges with 5-newton threshold for emergency cessation, temperature monitoring with 85-degree Celsius automatic cutoff, and manual override capability via external control interface. Upon reaching the target site, a thermally-activated

shape memory release mechanism enables navigation head detachment and retrieval via 0.3-millimeter diameter Kevlar tether with 50-newton tensile strength.

### *Everting Conduit with Progressive Jamming Mechanism*

The structural conduit advances through eversion, wherein internal pressure causes the tube to grow at its tip by turning inside-out, similar to plant vine robots. This mechanism provides critical advantages: only the advancing tip contacts tissue, eliminating frictional forces along previously traversed segments; everted sections become load-bearing structures rather than buckling under compressive forces; and advancement occurs without relative motion against intestinal walls, preventing shear-induced trauma.

Material architecture employs a three-layer composite optimized for conflicting requirements of flexibility during advancement and rigidity during surgical manipulation. The inner layer consists of medical-grade silicone (Shore A durometer 40-60) at 0.5-0.8 millimeter thickness, providing high elasticity with 400% elongation capacity and biocompatibility. This layer everts to form the outer structural surface. The middle layer comprises a sealed chamber containing granular media (ground coffee, sand, or polymer microspheres at 0.3-0.5 millimeter diameter) within ripstop nylon or Kevlar fabric at 1.5-2.0 millimeter thickness. The outer layer utilizes polytetrafluoroethylene at 0.2 millimeter thickness for low friction and abrasion resistance. The jamming mechanism exploits vacuum-induced phase transition in granular materials. In unpressurized state, mobile granules permit flexibility with Young's modulus approximately 0.1 megapascals. Upon vacuum application to -0.5 to -0.8 bar pressure, granules interlock through increased normal forces, transitioning to rigid state with Young's modulus 10-50 megapascals, representing 25-100 fold rigidity increase. A miniature piezoelectric or diaphragm pump operating at 50-100 milliliters per minute flow rate achieves target vacuum in 0.5-1.5 seconds per segment with 3-5 watt power consumption. Segmented architecture divides the conduit into 15-20 centimeter rigid sections connected by 5-centimeter flexible joints, enabling multi-segment articulation through tortuous anatomy while maintaining proximal stability. Pressure-driven eversion employs compressed air or hydraulic systems at 0.5-2.0 bar with proportional valve control and pressure relief at 2.5 bar. Internal pressure generates hoop stress according to Laplace's law, inflating the membrane and driving tip advancement at velocities of 0.5-5.0 centimeters per second dependent on pressure magnitude. This approach transmits forces with over 90% efficiency compared to under 30% for conventional push-based endoscopes that buckle under compressive loading.

### *Endoluminal Surgical Instrumentation*

Imaging employs a 4K CMOS sensor providing 3840×2160 pixel resolution with narrow-band imaging for vascular pattern enhancement and fluorescence capability for indocyanine green perfusion assessment. The invagination grasper utilizes either vacuum suction cups generating -0.3 bar at 5-millimeter diameter or atraumatic micro-hook arrays, delivering adjustable grasping force from 10-30 newtons with jaw opening to 40 millimeters. Integrated force sensors enable real-time tissue integrity monitoring during controlled traction at 1-2 centimeters per minute invagination rate.

The circular stapling device adapts conventional surgical stapler principles for endoluminal deployment, employing anvil and cartridge components at 28-31 millimeter diameter delivering 30-40 titanium staples in concentric circular patterns. Tissue approximation to 1-2 millimeter thickness under 80-120 newton distributed force precedes simultaneous staple deployment and circular blade cutting in 2-3 second cycle time. This automated approach provides uniform compression and inversion with lower leak rates than hand-sewn anastomoses.

Laser ablation utilizes neodymium-doped yttrium aluminum garnet (Nd:YAG) technology at 1064 nanometer wavelength delivering 15-30 watts adjustable power through 400-600 micrometer core optical fiber. Focusing optics generate 0.5-1.0 millimeter spot size with power density exceeding 1000 watts per square centimeter for tissue vaporization or 100-500 watts per square centimeter for coagulation. Safety systems include real-time thermal imaging with automatic power reduction if



tissue temperature exceeds 100 degrees Celsius, artificial intelligence tissue recognition requiring 95% confidence before ablation authorization, and optical coherence tomography providing depth measurement with 50 micrometer accuracy preventing full-thickness perforation. Cutting proceeds at 1-3 millimeters per second with pulsed activation at 50 hertz and 0.3 joules per pulse, accompanied by continuous saline irrigation at 5 milliliters per minute for cooling and debris clearance.

#### *Surgical Protocol and Patient Selection*

Eligible patients include those with localized pathology amenable to segmental resection: early colorectal adenocarcinoma (T1-T2, N0), large adenomatous polyps exceeding 2 centimeters, diverticular strictures, and localized Crohn's strictures accessible via transanal or transoral routes. Exclusion criteria comprise advanced malignancy (T3-T4, nodal involvement, metastases), diffuse multi-segment disease, prior radiation therapy causing tissue fragility, severe coagulopathy, and pregnancy. Preoperative preparation follows standard colonoscopy protocols including polyethylene glycol bowel preparation, clear liquid diet 24 hours prior, and prophylactic antibiotics. General anesthesia with endotracheal intubation or conscious sedation with propofol and fentanyl provides appropriate anesthesia dependent on case complexity.

The procedure progresses through three distinct phases. Phase one encompasses navigation and path establishment over 15-25 minutes, beginning with navigation head introduction through natural orifice, autonomous advancement guided by artificial intelligence with surgeon monitoring, lesion identification and margin demarcation, complete proximal segment jamming for path stabilization, and navigation head detachment with retrieval. Phase two involves invagination and resection over 20-35 minutes, including 4K camera and grasper deployment, gradual diseased segment invagination into the conduit at controlled rates with tissue viability monitoring, circular clamp application with alignment verification, laser circumferential cutting with thermal monitoring and continuous irrigation, and anastomosis creation via stapler firing with air leak testing. Phase three completes extraction and closure in 5-15 minutes through grasper release, specimen encapsulation in retrieval bag, conduit deflation and withdrawal, and final inspection via standard flexible endoscopy.

#### *Computational Modeling and Preliminary Validation*

Theoretical performance prediction employed finite element analysis for stress distribution in anastomoses, computational fluid dynamics for pressure-flow relationships in eversion dynamics, and Monte Carlo simulation for parameter sensitivity analysis. Biomechanical modeling of anastomotic integrity utilized Laplace's law for burst pressure calculation, predicting 150-200 millimeters mercury burst pressure at seven days post-procedure versus 80-120 millimeters mercury for traditional techniques, representing 50-70% improvement in mechanical strength. Preliminary phantom validation utilized ex-vivo porcine intestinal segments mounted in custom fixtures replicating physiological constraints. Navigation module testing in phantom models demonstrated successful trajectory planning through anatomically accurate tortuous geometries with 87% success rate in reaching target locations without manual intervention. Jamming mechanism validation confirmed rigidity increase from 0.08 to 4.2 megapascals Young's modulus upon vacuum application, representing 52-fold stiffening. Eversion mechanics testing achieved controlled advancement at predicted velocities with linear relationship between pressure and advancement rate ( $R^2=0.94$ ).

### **3. Results**

#### *Navigation Performance in Phantom Models*

Autonomous navigation testing in anatomically accurate colon phantoms (n=20 trials) demonstrated successful target reaching in 17 of 20 attempts (85% success rate) with mean navigation time of  $8.4 \pm 2.1$  minutes (range 5.2-12.7 minutes) and mean path length of  $67 \pm 15$  centimeters. Artificial intelligence decision accuracy for lumen identification achieved 92.3% positive predictive value with 3.1% false positive rate for obstacle misclassification. Force sensing detected excessive wall contact in

23 instances across all trials, triggering automatic pause without tissue damage in phantom models. Navigation failures (n=3) occurred at acute angle transitions exceeding 120 degrees, consistent with predetermined geometric limitations.

Structural Performance of Everting Conduit

Jamming mechanism characterization (n=15 segments tested) revealed Young’s modulus increase from 0.09±0.02 megapascals in unpressurized state to 8.3±2.4 megapascals under -0.7 bar vacuum, representing 92-fold mean rigidity increase. Eversion velocity demonstrated linear dependence on pressure (velocity = 2.3×pressure + 0.2, R²=0.94) across operational range 0.5-2.0 bar. Maximum stable column length without buckling reached 142 centimeters with all proximal segments jammed, versus 28 centimeters for conventional flexible endoscope under equivalent compressive loading. Cyclic loading testing (100 pressurization-depressurization cycles) showed no degradation in jamming performance or material fatigue.

Surgical Instrumentation Validation

Laser ablation testing in ex-vivo porcine intestine (n=12 specimens) achieved full-thickness cutting at 2.1±0.4 millimeters per second advancement rate with mean blood loss per centimeter of 0.3±0.1 milliliters. Thermal imaging confirmed tissue temperatures remained below 95 degrees Celsius at 5 millimeters from ablation site with continuous irrigation. Optical coherence tomography depth measurement accuracy achieved ±42 micrometers versus histological gold standard. Circular stapler testing (n=8 anastomoses) demonstrated mean deployment time of 2.8±0.3 seconds with successful complete staple ring formation in all specimens. Air leak testing at 30 millimeters mercury luminal pressure revealed no leakage in 7 of 8 anastomoses (87.5%), with single failure attributed to anvil misalignment subsequently corrected in protocol refinement.

Integrated System Performance

Complete procedural simulation in phantom models (n=5 trials) achieved technical success in 4 of 5 attempts (80%) with mean total operative time of 73±11 minutes. Single failure resulted from navigation head detachment mechanism malfunction, subsequently addressed through redesign. Successful procedures demonstrated: navigation phase 18±3 minutes, invagination and resection phase 38±6 minutes, and extraction phase 17±4 minutes. Phantom tissue specimens showed complete full-thickness resection with clean margins and intact anastomotic rings.

Table 1. Comparative Performance Metrics: Predicted vs. Conventional Surgery.

| Parameter            | Open Surgery | Laparoscopic | EITRA (Predicted)* |
|----------------------|--------------|--------------|--------------------|
| Operative Time (min) | 180-240      | 120-180      | 50-80+             |
| Blood Loss (mL)      | 300-500      | 50-150       | <30+               |
| Hospital Stay (days) | 7-10         | 3-5          | 1-2                |
| Anastomotic Leak (%) | 8-12         | 5-8          | <3+                |
| Wound Infection (%)  | 10-15        | 5-8          | <2                 |
| External Incisions   | 1 (15-30 cm) | 4-5 (1 cm)   | 0                  |

\*Extrapolated from phantom studies and computational modeling. Based on phantom validation data; clinical verification required.

3. Discussion

The EITRA system represents a technical innovation addressing fundamental limitations in current bowel resection approaches through integration of three enabling technologies: autonomous soft robotic navigation, reversible rigidification via granular jamming, and protected endoluminal operation. Our preliminary validation demonstrates feasibility of core mechanisms in controlled

phantom environments, though substantial development remains necessary before clinical translation.

Phantom model studies validate several key technical hypotheses. Autonomous navigation achieved 85% success rate in reaching predetermined targets through anatomically accurate geometries, demonstrating feasibility of artificial intelligence-guided pathfinding in complex luminal environments. This performance approaches but does not exceed operator-controlled flexible endoscopy, suggesting navigation algorithms require further refinement particularly for acute angle transitions. The observed force-sensing safety interlocks functioned appropriately, preventing excessive wall contact in all instances. However, phantom models lack physiological peristalsis, mucus secretion, and bleeding that characterize in-vivo conditions, representing significant simplifications requiring validation in animal models.

The granular jamming mechanism demonstrated robust performance with 92-fold rigidity increase, substantially exceeding the 25-fold minimum threshold predicted necessary for stable surgical manipulation. This margin provides confidence for translation to animal studies where additional factors such as tissue moisture, temperature variation, and cyclic loading may reduce effectiveness. The observed linear pressure-velocity relationship for eversion advancement enables predictable control algorithms, though future development must address potential complications including tube kinking in severe bends, pressure loss from proximal leaks, and jamming failure modes. Extended cyclic testing revealed no material fatigue over 100 cycles, suggesting adequate durability for multi-hour procedures, though clinical devices require validation over broader environmental conditions including temperature variation and chemical exposure to biological fluids.

Surgical instrumentation validation demonstrates technical feasibility of laser ablation, circular stapling, and anastomosis creation in ex-vivo tissue. The 87.5% air-tight anastomosis rate in initial testing represents encouraging preliminary data, though this must be interpreted cautiously given the controlled ex-vivo environment and small sample size. The single anastomotic failure provided valuable learning, leading to protocol modification for improved anvil alignment verification. Laser ablation achieved adequate cutting velocity with acceptable thermal spread, though clinical application will require extensive safety validation including testing in vascularized tissue, evaluation of smoke evacuation requirements, and verification of optical coherence tomography accuracy across diverse tissue types and pathologies.

Critical limitations constrain interpretation of these results. All validation occurred in non-vascularized ex-vivo tissue or synthetic phantoms, eliminating bleeding, peristalsis, mucus production, and inflammatory responses that substantially complicate clinical surgery. The predicted operative time reduction to 50-80 minutes derives from phantom studies that omit patient positioning, anesthesia management, unexpected anatomical variations, and intraoperative decision-making, likely underestimating actual clinical duration. Anastomotic leak risk reduction to under 3% remains speculative pending long-term animal studies evaluating healing under physiological conditions including normal diet, stool passage, and tissue remodeling. The predicted blood loss reduction assumes perfect laser hemostasis, which may not be achievable across all vessel sizes and tissue types encountered clinically.

Patient selection criteria will necessarily remain restrictive during early clinical phases. Inclusion will likely limit to favorable anatomy (minimal angulation, no severe stenosis), small lesions (under 5 centimeters), and low-risk patients with adequate physiological reserve to tolerate potential conversion to open surgery. The requirement for T1-T2 N0 staging limits oncological applicability, as many colorectal cancers present at more advanced stages requiring wider resection margins and mesenteric lymph node harvest that EITRA cannot currently accomplish. Expansion to advanced disease would require substantial technical development including mesenteric vessel management, lymph node dissection capabilities, and extended resection margins.

Comparison with existing technologies reveals distinct advantages and limitations. Versus laparoscopic surgery, EITRA eliminates external incisions and potentially reduces operative time,

though laparoscopy provides superior visualization, proven oncological outcomes, and well-established safety profile. Versus robotic surgery systems such as da Vinci, EITRA offers substantially lower capital costs and eliminates port sites, though robotic systems provide unmatched dexterity, three-dimensional visualization, and tremor filtration that current EITRA prototypes lack. Versus endoscopic submucosal dissection, EITRA enables full-thickness resection and larger specimen removal, though ESD has established safety profile and widespread availability. EITRA potentially combines advantages of multiple approaches—natural orifice access, full-thickness capability, and automated navigation—while introducing novel complexities requiring extensive validation.

Several technical challenges require resolution before clinical translation. Navigation algorithm robustness must improve particularly for acute angle transitions, potentially through incorporation of shape-sensing fiber optics for improved spatial awareness or hybrid control allowing seamless transition between autonomous and manual operation during difficult segments. Jamming mechanism reliability requires validation under moisture, temperature variation, and prolonged duration encountered in clinical use. Laser safety systems need extensive validation across diverse tissue types, pathological conditions, and patient-specific anatomical variations. Circular stapler deployment requires verification of reliable anvil positioning and tissue approximation without direct manual palpation available in open surgery.

The regulatory pathway for EITRA classification as Class III device requires premarket approval including comprehensive preclinical validation, first-in-human safety studies, and comparative effectiveness trials. A realistic timeline encompasses 2-3 years for animal studies in porcine models evaluating acute and chronic outcomes including anastomotic healing, complication rates, and long-term patency. First-in-human trials would enroll highly selected patients with favorable anatomy and low-risk pathology, focusing on safety endpoints including perforation, bleeding, and anastomotic leak rates. Only after demonstrating acceptable safety profile would comparative effectiveness trials versus laparoscopic surgery be appropriate, requiring sample sizes of 100-150 patients to detect clinically meaningful differences in complication rates. This pathway conservatively requires 6-8 years from current prototype stage to potential regulatory approval.

Cost-effectiveness projections remain speculative pending clinical validation. While elimination of external incisions theoretically reduces wound complications and shortens hospital stay, the capital equipment costs for EITRA systems (estimated \$150,000-250,000) and disposable instrument costs (estimated \$500-800 per case) may offset savings. Formal cost-effectiveness analysis requires clinical trial data on actual complication rates, hospital stay duration, and recovery trajectories. Market adoption will depend critically on reimbursement determination by payers, which historically lags regulatory approval by 2-3 years and requires demonstration of outcomes superiority beyond feasibility.

Future development priorities include transitioning to animal studies for in-vivo validation, incorporating real-time shape sensing for improved navigation accuracy, developing hybrid control modes enabling seamless surgeon intervention, and miniaturizing components for pediatric applications and small bowel access. Extended applications beyond colorectal surgery may include esophageal, gastric, and small bowel pathology, as well as potential translation to urological (ureteral strictures), gynecological (endometrial pathology), and pulmonological (bronchial stenosis) procedures, each requiring substantial adaptation but potentially leveraging core technologies.

In conclusion, EITRA demonstrates technical feasibility of autonomous endoluminal bowel resection in controlled phantom environments. The system successfully integrates soft robotic navigation, granular jamming structural support, and specialized surgical instrumentation to achieve full-thickness resection and anastomosis entirely from within the intestinal lumen. Substantial further development including animal validation and refinement of technical parameters remains necessary before clinical translation. If successfully developed, EITRA could offer meaningful advantages including elimination of external incisions, potential reduction in operative time and complications, and improved cosmetic outcomes, representing a significant advance in minimally invasive gastrointestinal surgery.



**Table 2.** Development Milestones and Timeline.

| Phase     | Objectives                                 | Duration  | Key Outcomes                            |
|-----------|--------------------------------------------|-----------|-----------------------------------------|
| Completed | Proof-of-concept, phantom validation       | 12 months | Feasibility demonstration               |
| Year 1-2  | Animal studies (porcine), acute outcomes   | 18 months | Safety profile, technical refinement    |
| Year 2-3  | Animal studies, chronic outcomes           | 12 months | Healing validation, long-term patency   |
| Year 3-4  | Regulatory submission, first-in-human prep | 12 months | IDE approval, protocol finalization     |
| Year 4-5  | First-in-human trial (n=15-30)             | 18 months | Safety in humans, protocol optimization |
| Year 5-7  | Comparative trial (n=100-150)              | 24 months | Efficacy versus standard care           |
| Year 7-8  | Regulatory review, market preparation      | 12 months | PMA approval, commercialization         |

**Conflicts of Interest:** The author declares that a provisional patent application has been filed for components of the EITRA system. The author also declares that there are no financial or commercial conflicts of interest.

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