Multiscale and Multiphysics Numerical Analysis of Enteric Nervous Signal Sensing in Wireless Capsule Endoscopy Applications

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***Abstract*—*Objectives:* Wireless Capsule Endoscopy (WCE) is a revolutionary technique for exploring gastrointestinal (GI) tract using an ingestible capsule, that offers valuable insights into poorly understood pathologies, such as functional gastric disorders. Recent studies have highlighted the rapid connections between specific enteroendocrine cell, known as Neuropods, and central nervous system via vagal synapses, which may play a role in functional gastric disorders. This paper presents a numerical study to verify the feasibility of performing neuronal sensing through WCE, focusing on the minimum enteric neural signal detectable by integrated electrodes. *Technology or Method:* Multiscale intestinal cavity models were developed in Comsol Multiphysics (v. 6.2), incorporating two capsule configurations, conformal ring electrodes, and reconstructed Neuropod action potentials derived from electrophysiological data. The electric signals were coupled with a readout circuit to model the acquisition of extracellular potentials. *Results:* The minimum detected signal is in the mV range, consistent with the sensitivity achievable by miniaturized electrode technologies suitable for ingestible devices. Multiscale validation showed strong agreement between millimetric and full-scale models in both waveform and amplitude. *Conclusions:* This study confirms the feasibility of enteric neuronal sensing using an ingestible capsule equipped with conformal electrodes. *Clinical or Biological Impact:* Using this technology for enteric neural sensing could advance our understanding of functional gastric disorders, the gut-brain axis communication and related cognitive functions.**

***Index Terms*—Wireless capsule endoscopy, enteric neuronal sensing, ingestible devices, numerical modeling, enteric nervous system.**

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I. Introduction

Over the past few decades, endoscopic examinations have increasingly moved beyond wired instruments thanks to Wireless Capsule Endoscopy (WCE) [1], [2], [3], [4], [5]. This method involves a miniaturized, ingestible and biocompatible pill [6], incorporating: a battery, sensors for measuring biological parameters, one or more cameras, a microprocessor, and an ingestible transmitter [7].

Currently, the standard functionalities of the commercial capsules are the measurement of pH, pressure, temperature, intestinal gases, and hemoglobin levels [7], [8], [9]. In parallel with these consolidated functions, several research groups have explored extensions of WCE toward both diagnostic and therapeutic applications. Srinivasan and colleagues presented a robotic capsule for drug delivery purposes (RoboCap) [10]. The capsule was designed to clear the intestinal mucus barrier and improve Vancomycin and Insulin absorption [10]. The same group developed a vibrating capsule (VIBES), targeting gastric mechanoreceptors to control the satiety sensation [11]. A fluid-wicking capsule (FLASH) for localized hormone modulation has also been proposed as an alternative to invasive gastric stimulation [12]. In diagnostics, detecting short-lived inflammatory biomarkers directly within the GI tract remains a key challenge. A highly innovative ingestible capsule, combining genetically engineered probiotic biosensors with a custom-designed, low-power optoelectronic system has been proposed [13]. In another study, Traverso and colleagues proposed a vitals-monitoring (VM) pill for ballistic monitoring of respiratory and cardiac activity [14]. Furthermore, given the increasingly recognized gut microbiome role in human health and disease, novel magnetically-controlled capsule-based devices enabling targeted, minimally invasive microbiota sampling have been explored [15].

Beyond biochemical sensing, recent studies have also investigated advanced imaging approaches to enhance WCE diagnostic capabilities. In particular, hyperspectral imaging–based enhancement techniques have been proposed to improve mucosal contrast and visualization in WCE, enabling the extraction of additional spectral information from the tissue [16]. Complementary approaches combining hyperspectral data with deep learning have also been explored; for example, CycleGAN-based simulations of narrowband imaging have demonstrated

potential for improving the detection of early esophageal cancer by enhancing subtle mucosal and vascular patterns [17].

Despite these technological developments, no commercial capsule currently incorporates electrodes capable of sensing enteric electrical activity [18], [19]. As the capsule travels through the GI tract, it encounters a complex network of neurons and other cells types, that comprise the enteric nervous system (ENS) [20]. The enteric neurons work in synergy with other non-neuronal cells: enteroendocrine cells (EECs), located inside the intestinal villi, are specialized in detecting the luminal content, producing and releasing hormones, modulating a variety of physiological GI activities [21]. Recently, it has been highlighted that a subgroup of EECs, called "Neuropod", can relay fast, spike-like signals to vagal afferents [22], [23], forming one of the shortest-latency communication routes between the gut and the central nervous system (CNS) [24], [25]. This suggests their possible key role in the gut-brain axis [24], providing an excellent therapeutic target not only for immunological and digestive pathologies [23], [25], but also for functional GI diseases.

Despite the rapid evolution of WCE technologies, existing devices and modeling studies have primarily focused on chemical, mechanical, optical, or physiological sensing modalities. To the best of the authors' knowledge, a quantitative bioelectromagnetic analysis addressing the feasibility of neuronal signal sensing within the GI environment has not yet been systematically explored. However, such an analysis is a necessary preliminary step for the rational design of future intelligent capsules capable of interfacing with the ENS [26]. In fact, directly capturing these events would provide electrophysiological information that current WCE platforms cannot provide, thereby motivating the development of sensing-oriented capsule models as explored within the PING project, funded by Lazio Region in Italy. In particular, the present study focuses on the numerical feasibility of such signal detection by estimating the minimum detectable signal level. To this aim, a highly detailed millimetric unit was developed, capturing the realistic villus microstructure and the 3D distribution of Neuropods. This model offers an accurate picture of the electrical environment close to the capsule electrodes. A second, full-scale model was then introduced to extend the analysis to the entire capsule geometry, using simplified tissue and source representations to ensure computational feasibility while preserving the key electrophysiological features predicted by the high-fidelity millimetric model. In this regard, the Neuropod action potential, obtained from electrophysiological measurements [27], was reconstructed and used as the input for the numerical analysis in Comsol Multiphysics (v. 6.2). The following sections describe intestinal models of different complexity and the multiphysics framework adopted to simulate the activation of Neuropod sources together with the electrode-based acquisition circuitry.

II. Methods and Procedures

A. Reconstruction Procedure of the Neuronal Signal Produced By the Neuropods

The action potential used in this study was taken from the electrophysiological measurements reported in [27] for a rat Enterochromaffin cell, a subtype of EECs. Originally the trace available was not directly usable for numerical simulations, as its discretized form appeared irregular and partially fragmented. For this reason, a three-step processing pipeline was applied to obtain a consistent and simulation-ready signal (Fig. 1). First, the trace was smoothed to reduce discontinuities and remove fluctuations not representative of the biological event ("Step 1"). A baseline noise component was then reconstructed ("Step 2") by filtering white noise at the cutoff frequency estimated from the power spectrum of the measured signal (100 Hz) and scaling it to match the variance of the original baseline. Finally, the reconstructed noise was added to the smoothed spike, and the resulting trace underwent down-sampling and a second smoothing ("Step 3"), yielding the neuronal signal used as input in the numerical models.

B. Local Millimetric Model and Electrode Representation

To characterize the electrical conditions at the scale of the intestinal villi, a local millimetric model was developed, following the reduction and optimization strategy shown in Fig. 2. As a reference geometry, the capsule currently being explored within the PING project is made of Alumina, a biocompatible material, and it has a length of approximately 12 mm and a diameter of 6 mm. Two ring-shaped electrodes, conformal to the capsule surface, are integrated. These electrodes consist of thin gold bands with a thickness of about 20 μm, a width of a few hundred micrometers, and a comparable interelectrode spacing. To limit the computational burden while retaining the relevant microscale features, only a small portion of the intestinal tract was modeled, as illustrated in Fig. 2. The resulting domain is a box with 1 mm $\times$ 1 mm cross section and a height of 1.5 cm, containing the intestinal wall of 1.2 mm thickness [28], and a mucosal surface enlarged by the presence of villi. This "millimetric model" (Panel (b), Fig. 2), includes a 6 mm high segment of the capsule (corresponding to its diameter) and the segments of the two ring electrodes that fall within the local domain. The villi were modeled as elongated tapered structures extending from the mucosal surface, arranged in a uniform pattern to approximate the organization of the intestinal wall, with a height of 0.5 mm. Neuropods were represented as spherical sources with a radius of 0.015 mm [29], distributed within the villi and located close to their surfaces, with a density of approximately 25 cells/mm^2 [30]. Their placement reflects the local microstructure, while the number of active sources (i.e., 50) was chosen to balance biological realism and computational feasibility. This millimetric model acts as a representative simulative unit, a "local core sample", which can be replicated through the use of continuity boundary conditions in the AC/DC *Electric Currents* module in Comsol Multiphysics (for further details see Supplementary Material, section I).

Two relative positions of the capsule were considered. In *case 1* (Panel (b), Fig. 2), the capsule lies close to the mucosal surface, representative of a horizontal intestinal segment where adhesion due to gravity is plausible. In *case 2* (Panel (c), Fig. 2), the capsule is centered within the lumen, representative of a vertical segment where suspension in the middle is more likely.

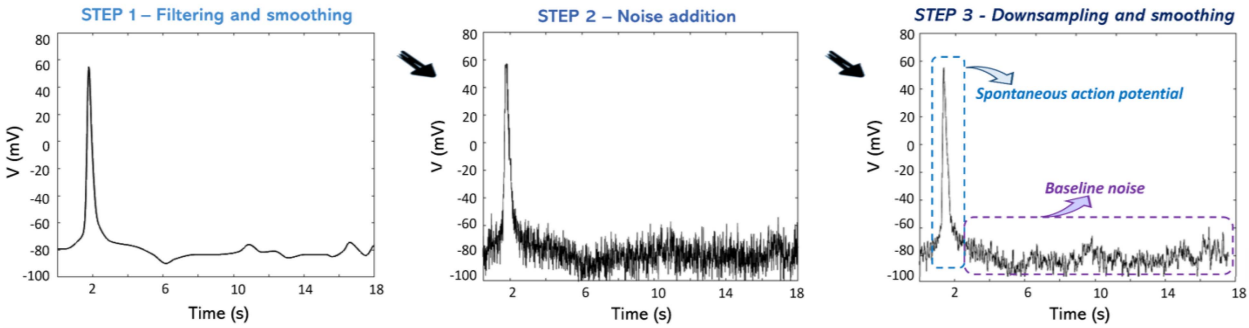

Fig. 1. Overview of the signal reconstruction procedure: smoothing of the original EECs' action potential trace from [27] ("Step 1"); addition of the action potential baseline noise ("Step 2") and further down sampling and smoothing ("Step 3"), to obtain the final reconstructed neuronal signal.

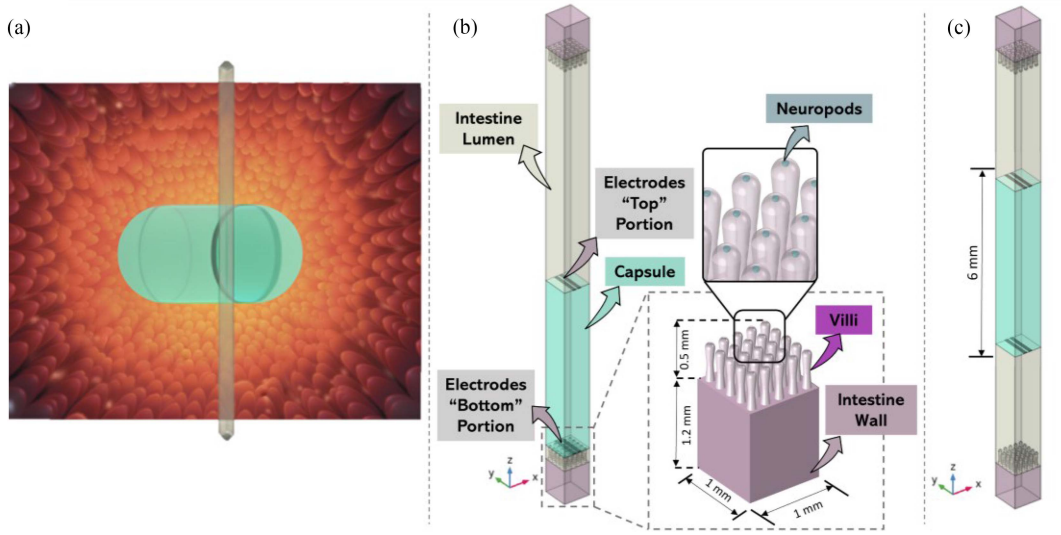

Fig. 2. Optimization strategy used to define the local millimetric model. (a) Full alumina capsule geometry, with integrated golden ring electrodes, and surrounding intestinal wall. (b) Extracted millimetric "core sample" with villi, local portion of the capsule, and the corresponding electrode segments. The villi are depicted as tapered structures with a height of 0.5 mm, and the neuropods are represented as spheres with a radius of 0.015 mm, located inside the villi. (c) Alternative capsule position at the center of the lumen.

TABLE I
MATERIALS AND DIELECTRIC PROPERTIES ASSIGNED IN BOTH MILLIMETRIC AND FULL-SCALE INTESTINAL MODELS

Materials	*Electrical conductivity σ [S/m]*	*Relative permittivity ε_r*	*Reference*
Lumen	$4.61 \cdot 10^{-1}$	$9.33 \cdot 10^{6}$	[31]
Intestinal Wall	$1.64 \cdot 10^{-1}$	$8.73 \cdot 10^{5}$	[31]
Neuron Membrane	$1.1 \cdot 10^{-7}$	11.7	[32]–[34]
Cytoplasm	0.3	67	[32]–[34]
Gold	$45.6 \cdot 10^{6}$	1	[36]
Alumina	$1.09 \cdot 10^{-7}$	9.8	[35]

All the material properties assigned are reported in Table I, specifically: intestinal wall and lumen properties were taken from the LF-IT'IS Database [31]; typical neuronal cytoplasm and plasma membrane materials were assigned to Neuropod cells domains and boundaries, respectively [32], [33], [34]; the capsule portion was modeled using alumina [35], and the electrode segments using gold [36]. The reconstructed Neuropod action potential was applied to the spherical cells using a Terminal in the *Electric Currents* module to compute the resulting electrical quantities in the simulation domain (as described in detail in Supplementary Material, section I).

C. Building a Full-Scale Intestinal Model

A full-scale intestinal model was developed to extend the analysis from the local millimetric unit to the entire capsule geometry and to evaluate the electrical potential distribution along the full circumference of the sensing electrodes. In the

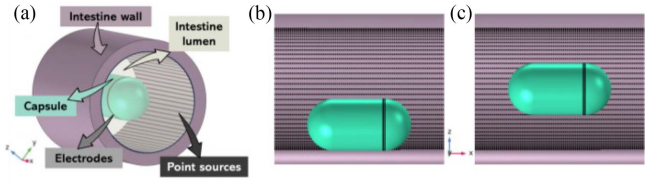

Fig. 3. (a) 3D view of the full-scale intestinal model, where Neuropods are represented as point-like sources. The capsule is shown in two configurations: (b) Near the intestinal wall and (c) at the center of the lumen, illustrated on a zx plane.

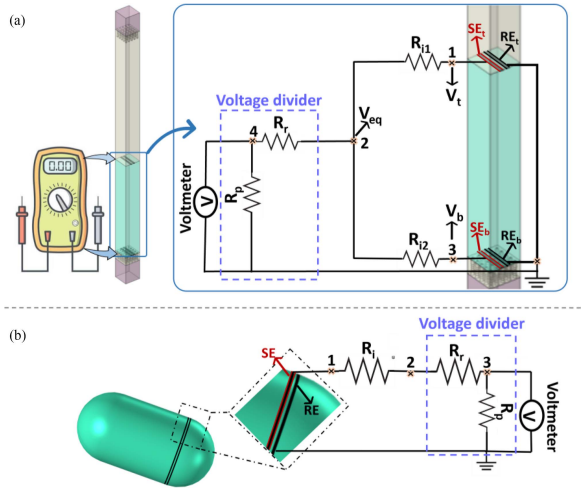

Fig. 4. Example of the readout circuit used to compute the potential at the sensing electrode. In both the millimetric (a) and full-scale (b) models, the local electrode potentials are first computed in the *Electric Currents* interface and then passed to the *Electric Circuits* interface. In the millimetric model, the sensing electrode is split into two portions, corresponding to nodes 1 and 3, which provide the voltages V_b and V_t. These are modeled as two parallel voltage sources and connected to a voltage divider where the potential across the partition resistor R_p is measured. In the full-scale model, a single potential value is obtained from the sensing ring and used as a single voltage source feeding the same voltage divider configuration.

full-scale model, the intestinal cavity is represented as a cylinder with a diameter of 1.5 cm, according to the millimetric model dimensions. Given the larger spatial scale, the Neuropod sources were represented as point-like elements distributed according to the same surface density used in the millimetric model, while the villi were omitted to maintain computational feasibility (Panel (a), Fig. 3). Consequently, the intestinal wall has a thickness of 1.7 mm, resulting in the sum of the height of the intestine wall and villi in the millimetric model. The capsule and ring electrodes geometry and dimension are in line with the project requirements explained in *Section B*. Two positions of the pill were considered in analogy with the millimetric model (Panels (b), (c), Fig. 3). The model allows to consider a phase shifts between the sources, related to the action potential propagation along the cavity that can be neglected in the millimetric model. According to the literature, the action potentials propagation speed in enteric neurons is 0.04 m/s [37]. A deterministic phase shift t_0 was introduced along the x-axis to emulate propagation in a preferred direction. An additional stochastic latency r_n uniformly distributed within $\pm$ 12 ms, assigned to each source to reproduce the intrinsic variability of sodium and potassium channel activation [38]. The material properties are assigned consistently with the millimetric model and are reported in Table I.

D. Multiphysics Implementation to Read the Voltage on the Sensing Electrode

To compute the effective voltage difference (ΔV) between the sensing and reference electrodes, the *Electric Currents* and *Electric Circuits* interfaces were coupled. In this framework, the local electric potentials on the capsule electrodes are computed in the *Electric Currents* module and then passed as inputs to the circuit model. In the millimetric model, each ring electrode is split into an upper and a lower portion, reported in Fig. 4, Panel (a) as: SE_t and SE_b, for the top and bottom sensing electrode portions, respectively, and highlighted in red; RE_t and RE_b, for the top and bottom reference electrode portions, respectively, and highlighted in black. The *Electric Currents* interface provides the electric potential at SE_t and SE_b, labelled as nodes 1 and 3 in Panel (a), Fig. 4. These potentials correspond to the values V_b,at node 3, and V_t, at node 1, used in the circuit representation. The two portions of the reference electrode, RE_t and RE_b, are assigned to node 0 of the circuit, corresponding to the ground. V_b and V_t were therefore implemented in the *Electric Circuits* interface as two parallel voltage sources, each associated with an internal resistance of 1 kΩ. This reflects the model symmetry and the fact that each segment of the gold ring behaves as an equipotential surface. The corresponding equivalent potential applied to the circuit input at node 2 is $V_{eq} = (V_b + V_t)/2$. This equivalent voltage feeds a simple voltage divider connected at node 2 of the circuit (Fig. 4, Panel (a)), in which R_r is a reading resistor, whereas R_p is the partition resistor. The potential across R_p is monitored using a voltmeter. The circuit is not intended to represent a final readout system; rather, it provides a conceptual example of how the electrode output could interface with an electronic stage, as a voltage divider.

In the full-scale intestinal model (panel (b), Fig. 4), the *Electric Currents* interface provides a single potential value on the sensing ring (SE), at node 1, relative to the reference electrode (RE), node 0. This value is passed to the *Electric Circuits* interface as a single voltage source, connected through its internal resistance R_i to a voltage divider at node 2, characterized as in the millimetric model case. The voltage across resistor R_p is recorded through a voltmeter. Further details on the readout circuit implementation for both millimetric and full-scale model are reported in Section II of Supplementary Material, with the equivalent circuit in LTspice in Fig. S2 and S3.

III. Results

A. Analysis of the Electric Voltage Induced on the Electrodes in the Millimetric and Full-Scale Models

Fig. 5 shows electric potential V maps at the action potential peak, at t = 1.76 s, for *case 1*, where the pill is positioned close to the intestinal wall (Panel (a)), and *case 2*, in which the capsule

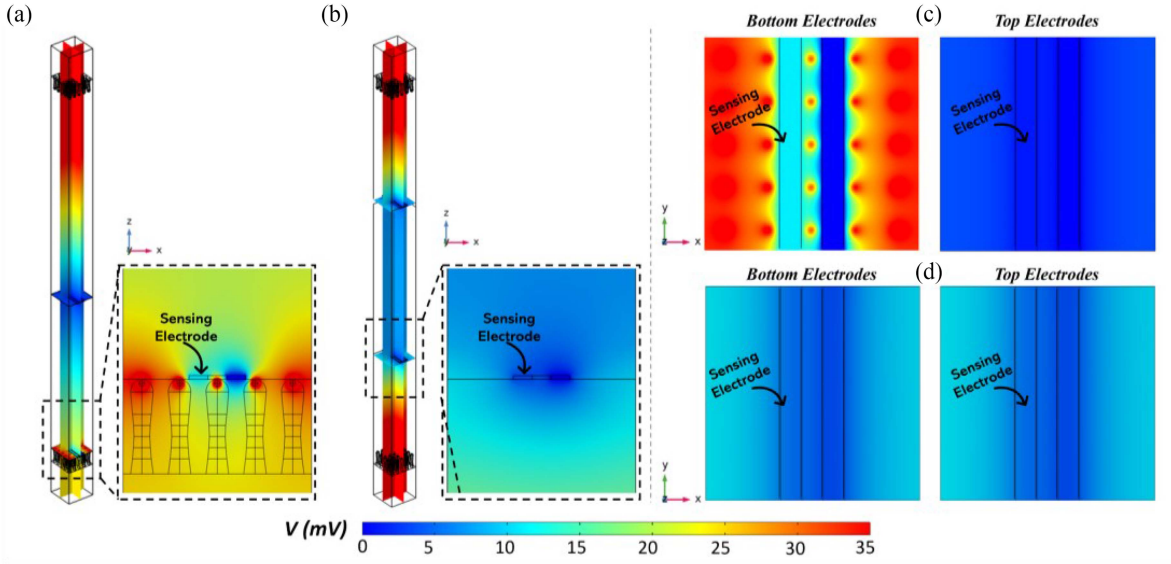

Fig. 5. Electric potential V distributions of the millimetric model, at the peak of the Neuropod action potential (t = 1.76 s), on zx planes for (a) *case 1* and (b) *case 2*, and xy planes for (c) *case 1* and (d) *case 2*.

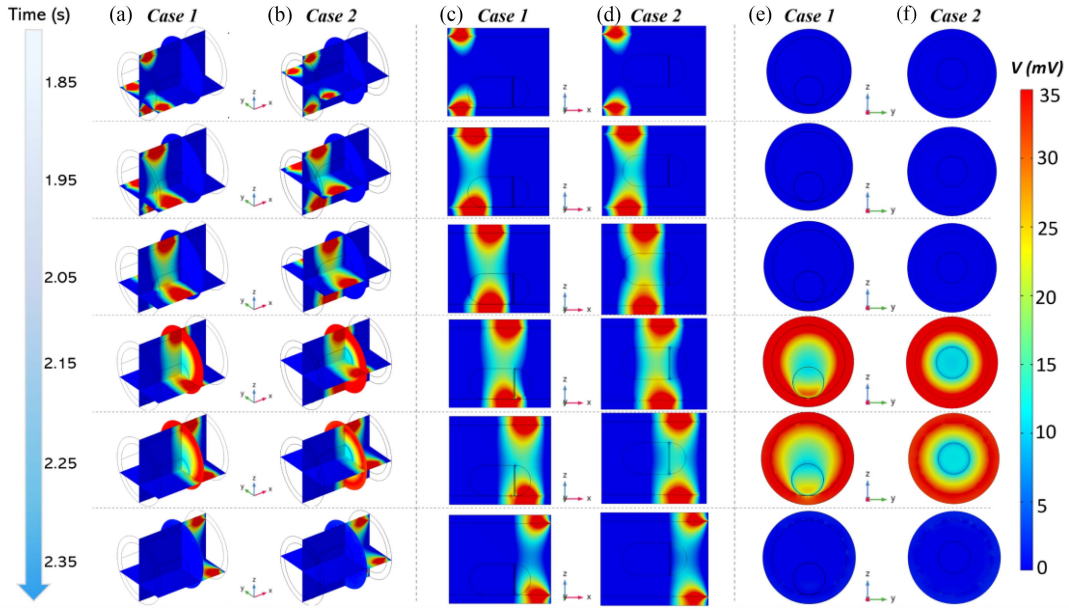

Fig. 6. Electric potential V distribution of the full-scale intestinal model at different time points, showing the propagation of the signal along the intestinal cavity in 3D views for (a) *case 1* and (b) *case 2,* (c), (d) zx-plane sections crossing the capsule center, (e), (f) zy-plane sections aligned with the x-coordinate of the recording electrode. Temporal evolution reflects the imposed latencies in Neuropod activation, resulting in delayed arrival of the signal at the electrodes.

is located at the lumen center (Panel (b)). Each map provides a 3D view of the V induced inside the model, together with a zoom on the electrode region in the central zx cross-section. For *case 1*, V on the bottom sensing electrode portion reaches approximately 11 mV, in contrast V on the top sensing portion is about 1 mV. This behavior is further confirmed by the xy plane maps at z-coordinates intersecting the top and bottom electrode portions: at z = 9.73 mm and z = 3.75 mm from the villi peak in *case 1* (Panel (c)), z = 0.01 mm and z = 5.99 mm in *case 2* (Panel (d)). From these maps, the potential peak in *case 2* is approximately 2.5 mV on both electrodes portions. The readout circuit acquires these voltages, acting as a voltage divider that halves the signal amplitude.

The V maps of the full-scale model are reported in Fig. 6, to show the spatial propagation of the signal along the intestinal cavity. For both capsule's positions, 3D maps are shown at different time points (Panels (a) and (b)), together with the zx (Panels (c) and (d)) and zy planes (Panels (e) and (f)). The selected zy plane passes through the x-coordinate of the recording electrode center, whereas the zx plane intersects the

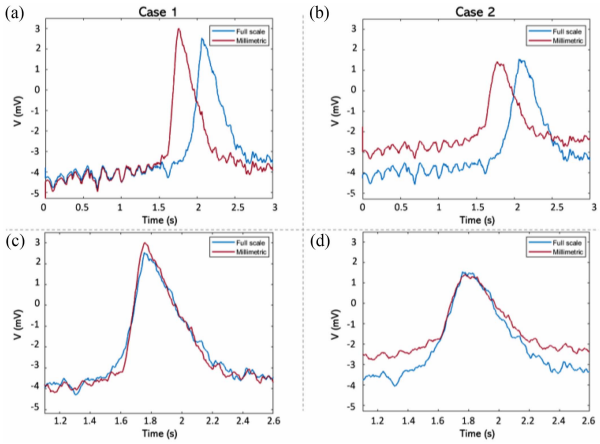

Fig. 7. Time evolution of the electric potential V acquired by the sensing electrodes in the millimetric (in red) and full-scale models (in blue) for *case 1* (a) and *case 2* (b). Panels (c) and (d) show magnified and time-aligned views of the corresponding waveforms, allowing a direct comparison of their shapes. The two models exhibit similar signal dynamics and amplitudes, with the full-scale configuration showing a short delay due to propagation effects.

capsule at the y-coordinate of its center. These maps show the propagation of the signal generated by the Neuropods, which do not fire simultaneously. The introduction of latency caused a shift, with the signal reaching the electrodes from t = 2.14 s. As expected and consistent with the millimetric model, V is higher in *case 1* than in *case 2*.

B. Electrodes Read-Out: a Comparison Between Millimetric and Full-Scale Intestinal Models

As shown in Fig. 7, the evolution in time of the electric potentials acquired by the voltage divider of the reading circuit is consistent across millimetric and full-scale models for both capsule positions. In *case 1*, the recorded potential ranges from approximately −5 mV to a peak value of 2.5 mV and 3 mV in the millimetric and full-scale models, respectively (Panel (a)), with a delay of 0.4 s in the full-scale. In *case 2*, the peak amplitude decreases to roughly 1.5 mV, with a slightly reduced temporal dynamics in the millimetric model (Panel (b)). The close similarity between the two waveforms confirms that extending the modeling domain from the local to the global scale does not affect the main features of the signal captured by the readout circuit. The zoomed and time-aligned views plots, in Panels (c) and (d), show that the millimetric model accurately reproduces the shape and timing of the full-scale response. These results confirm that the integrated readout circuit is able to capture the enteric electrical signal in both modeling configurations.

To evaluate the detectability of the captured signal in a realistic noisy environment [39], an additional analysis was carried out assuming a discriminability index d' = 2, corresponding to a high probability of distinguishing the signal from background noise. Under this assumption, the noise variance should remain below 2.1 mV^2 and 1.8 mV^2 for the millimetric and full-scale models, respectively, in *case 1*. In *case 2*, where the signal amplitude is lower, the corresponding thresholds become 1.1 mV^2 and 1.6 mV^2. The noise limits predicted by the two models are comparable and fall within a range consistent with expected values in the intestinal environment. This is supported by recent in vivo evidence from ingestible gastric devices, which successfully recorded mV range biopotentials despite significant physiological artifacts, suggesting that intestinal recordings are expected to be even less affected by noise [40].

IV. Discussion

WCE is an established platform for minimally invasive GI diagnostics [1], [2], [3], [4], [5]. However, no current capsule system integrates electrodes for direct recording enteric electrical activity, that could provide new insights into gut–brain communication. Neuropods, a specialized subtype of EECs, form a direct pathway to the central nervous system [22], [23], [24], [25]. To assess the feasibility of detecting Neuropod-generated action potentials using an ingestible device, we developed a multiscale numerical model reproducing the capsule and its surrounding intestinal environment. The input neuronal signal was reconstructed from electrophysiological measurements in [27], and its interaction with the capsule's electrode system was assessed through a coupled electromagnetic and electric-circuit simulation framework. The millimetric model provided a high degree of structural realism, including 3D villi morphology, multiple spatial scales, and a dense distribution of active Neuropod sources. This configuration allowed a rigorous assessment of the sensing mechanism, while propagation effects were negligible due to the limited spatial extent. Because each ring electrode was represented by two segments, it was necessary to verify that their parallel connection faithfully reproduced the behavior of an equipotential ring. This step ensured the reliability of the millimetric model, which has microstructural resolution not computationally attainable at the full intestinal scale. The full-scale model was therefore implemented to include the complete cylindrical geometry and to simulate realistic propagation delays along the intestinal wall.

Results showed strong agreement between the two models in both waveform shape and amplitude, with the expected temporal shift emerging only in the full-scale configuration. The recorded potentials, in the mV range, are within the measurable limits of the electrodes technology. Overall, the findings confirm the numerical feasibility of detecting enteric neuronal activity with an ingestible capsule equipped with ring electrodes.

To further evaluate the robustness of the proposed sensing configuration under realistic physiological and operational variability, an additional variability analysis was performed on the full-scale model, through the Uncertainty Quantification Module in Comsol Multiphysics. Variability was introduced in several parameters that may influence the recorded neuronal signal during GI transit. In particular, the propagation speed of the enteric action potential was varied in a range from 0.033 m/s to 0.04 m/s [37], resulting in a maximum decrease in the detected peak amplitude of approximately 15.4% and 30.7%, for *case 1* and *case 2*, respectively. The electrical conductivity of the intestinal lumen was also varied according to the low-frequency range reported in the IT'IS database [31], representative of intestinal

and colonic contents, leading to a variation of the detected peak value of about 26% and 14%, in *case 1* and *case 2*, respectively. Furthermore, the possible effect of capsule orientation during transit was investigated by introducing tilt angles up to 10°, which produced in *case 1* deviations below approximately 9.2% with respect to the reference configuration, and 13.3% in *case 2*. Finally, the potential impact of biofouling at the electrode–tissue interface, caused by increases in contact impedance due to possible adsorption of biological material, was emulated by introducing a 10% increase in the R_r of the readout circuit, resulting in a maximum reduction in the detected peak amplitude of 18.7% and 12%, in *case 1* and *case 2*, respectively. Despite these variations, the predicted neuronal signals remained in the mV range and therefore within the feasibility range for detection using miniaturized electrodes, suitable for ingestible capsule systems. A detailed description of the uncertainty quantification analyses is provided in Section IV of the Supplementary Material.

Furthermore, an additional sensitivity analysis considering 50% and 60% reductions in the number of active sources, related to possible irritable bowel syndrome and inflammatory bowel disease, is reported in Section III of Supplementary Material. The analysis shows that even with a 50% reduction in the peak amplitude, the acquired neuronal signal remains within the range compatible with the sensing feasibility.

Beyond feasibility, the proposed multiscale modeling framework provides a design-oriented tool to support the development of future intelligent capsule-based sensing systems. By linking tissue-scale electrophysiological sources to electrode-level signals, the model allows estimation of expected signal amplitudes, assessment of the impact of capsule position and electrode configuration. Overall, this framework provides a multiscale computational approach, enabling a physically based estimation of induced potentials, while maintaining a simplified and conceptual representation of the readout stage. Importantly, the objective of this work is not the design or optimization of a final electronic readout system, but rather the development of a consistent modeling framework capable of predicting the electrical signals generated at the electrode level and assessing their feasibility within realistic sensing constraints. In this sense, the circuit representation should be interpreted as a minimal and illustrative interface rather than a definitive electronic implementation.

Given their role in short-latency vagal signaling, the ability to sense Neuropod-related activity may offer a way to probe the rapid sensory pathways of the gut–brain axis within a minimally invasive platform. *In-silico* exploration of sensing strategies and design choices supports the rational design of next-generation bioelectronic WCE systems targeting enteric neural interfaces.

V. Conclusion

This work presented a multiscale numerical framework to quantitatively assess the feasibility of sensing enteric neuronal activity using an ingestible capsule equipped with ring electrodes, representing a significant step forward in GI diagnostics. The strong agreement between the millimetric and full-scale models confirms that the proposed sensing configuration can detect low-amplitude Neuropod-generated potentials. Overall, the modeling approach provides a robust and reliable tool for the design and performance evaluation of future bioelectronic WCE systems, enabling the integration of neural sensing functionalities to support advanced research on gut–brain communication and related neuro-gastroenterological functions.

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