Vibrating Micro-Capsule as an Autonomous Device for *in-situ* Endoscopic Scan and Body Tissue Characterization

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Abstract: – This work concerns the implementation of a diagnostic technique for the digestive system using a device designed based on a spherical vibrating capsule of 1 cm in diameter and autonomous by its onboard electronics. For local scanning, this device is also equipped with a network of high-frequency optimized sensors. Depending on the desired diagnosis, this device can adapt its electromechanical characteristics to the nature of the application in transmission and/or simultaneous reception. It is also designed for network configuration to provide a 3D mapping of the acoustic properties of the environment under investigation (biological tissues).

Key-Words: - Pill resonator, Acoustic Sensor, Tissues Characterization, Endoscopic scan, Embedded electronic, Soft diagnosis, Micro-System.

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1 Introduction

Today, our lives are assisted by intelligent concepts thus guiding our gestures, our movements, and even our way of life. In multiple areas, studies have focused on the adaptation and optimization of devices integrating into new models of socio-technological interaction involving the different actors of society in areas as diverse as health, comfort, and safety. Indeed, considerable advances in digital technologies coupled with the needs of the population are leading us to redefine our modern environment. This context is subject to constant evolution, both on a daily level and on a technological level. Estimating "socio-technological" coherence means being able to respond to growing demand for specific needs in care, well-being, and comfort which are the virtues sought for the development of cross-skills and harmonization between the actors concerned. In the case of this study, the distribution of a biocompatible sensor network within the body is at the center point of concern in order to understand the behavior of tissues in interaction with the mechanical wave. The clinical environment makes it difficult to acquire multiple physiological data except a few techniques, often wired (probes) or radiation (MRI) which require patient specificity to allow continuous monitoring of a dynamic process in its entirety. Many of the studies have addressed endoscopic ultrasound applications, the majority of which used wired systems, [1], [2], [3], [4]. It is in this context that this study aims to implement a non-wired diagnostic micro-system adapted to specific needs such as the effects of environmental aggressiveness to correlate wave/tissue interactions with possible metabolic modifications. Indeed, the need for a technology exploiting autonomous sensors led us to develop a miniaturized spherical resonator to characterize in-vivo the mechanical behavior of biological tissues under a wide frequency band. The study aims to develop an acoustic/ultrasonic system based on the design and implementation of a miniaturized biocompatible capsule with on-board electronics (Figure 1) which will serve as an ultrasound pill as well for the characterization of tissues in a low-frequency band for endoscopic exploration at higher frequencies.

The study of this device was carried out step by step, [5], [6], starting first with the evaluation of the vibrational behavior of the pill. Then, energy autonomy was addressed by the integration of electronics dedicated to energy harvesting and storage, focusing on the energy balance and conversion (Figure 2). This approach made it possible to logically schedule the operation of several tasks in parallel or sequentially such as the selection of the vibration mode of the structure, the transmission/reception mode (characterization and scanning), data storage, and acoustic telecommunications through the media as well as an energy optimization which gives it operating autonomy rarely found in current screening systems.

The technology of resonators concept makes their use in a three-dimensional network configuration possible. Each sensor is identifiable either by the choice of the resonance frequency of its structure or by digital coding of the acoustic transmission frames. A network of capsules randomly distributed in complex environments could provide useful information on the properties of a dynamic bio-system.

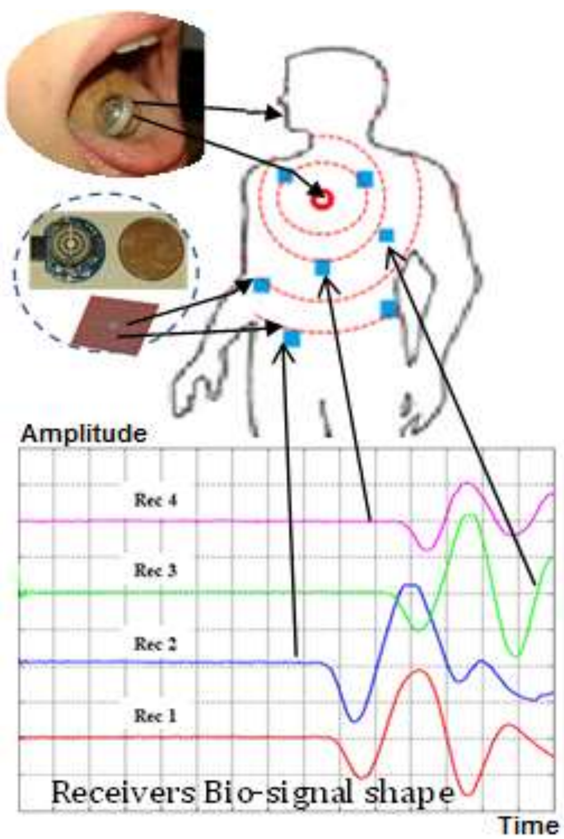

Fig. 1: Schematic illustration showing the principle of the acoustic pill: the red dot is the endoscopic position of the transmitting vibrating pill and the blue dots represent the external annular resonators used as receivers

2 Resonator Devices

2.1 Integrated Transmitter Capsule

For macroscopic characterization which requires a low frequency to avoid the attenuation phenomenon in transmission waves, the structure of the capsule is excited by a ring having piezoelectric properties set under stress on sandwiched between the two bio-compatible half-spheres representing the hollow capsule in its entirety. This arrangement allowed us to resonate a pill 1 cm in diameter in the low frequency band, which transforms the capsule into a point vibrational source generating a spherical wave in the medium.

The tests focused on a hollow plexiglass capsule with 8mm as an internal diameter and 2 mm as a thickness. A 0.5 mm thick piezoelectric ring is wedged between the two hemispheres (Figure 2) which offers a good compromise for a resonance in breathing mode at 32 kHz. This frequency allows the vibrational exploration of complex, highly dispersive environments and the transmission of information acoustically.

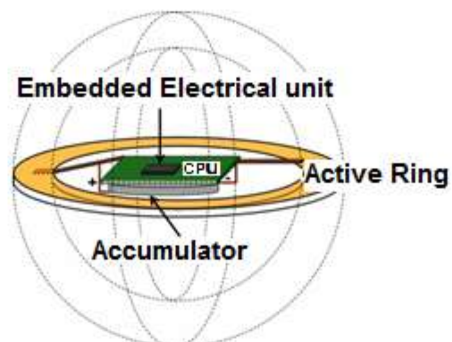

Fig. 2: Components of the vibrating pill, [6]

2.2 Vibration by Elongation: Fundamental Mode

1) State of the art on the use of a spherical shape.

Few works have exploited the vibrational effects of a spherical or almost spherical resonator. Some of their, [7], [8], are among those who were interested in the miniaturization of a quasi-spherical vibration sensor for an application relating to the gastrointestinal tract by ultrasound. They focused on an elliptical-shaped resonator measuring 1 cm x 2.5 cm whose active elements are actuated by an external source. For the same purpose, some researchers used a wired ultrasound concept in his work to evaluate the feasibility of endoscopy using a miniaturized ultrasound capsule, [9], and other was oriented towards the development of a theoretical formalism by finite elements of an ultrasound concept based on spherical resonators, [10], [11].

2) Analytical approach
Numerous studies have been carried out on the mechanical behavior of spherical shells, particularly on axisymmetric modes. Studies have concerned the field of macrostructure, [12], [13], [14], [15], [16], [17], [18], [19], targeting the effects of the vibration of a macrospherical shell subjected to transverse shears and rotational inertias.

From this work, by using the Lagrangian formulation resulting from the fundamental theory of Love, we have established the equations of motion of a spherical shell. In free motion without constraints on an undamped structure, the Lagrangian feature L is expressed by the kinetic energy T and the potential energy U under the following expression:

$$\mathbf{L} = \mathbf{T} - \mathbf{U} \quad (1)$$

Based on Hamilton's approach applied to a dynamic system in free vibration over $t_1 \leq t \leq t_2$, the associated equations of motion satisfy the following condition:

$$\boldsymbol{\delta}\mathbf{A} = \boldsymbol{\delta}\int_{t_1}^{t_2}\mathbf{L}\mathbf{dt} = \boldsymbol{\delta}\int_{t_1}^{t_2}(\mathbf{T}-\mathbf{U})\mathbf{dt} = \mathbf{0} \quad (2)$$

In the case of a spherical shape, T is given by:

$$\mathbf{T} = \frac{1}{2}\boldsymbol{\rho}\mathbf{h}\iint\left[\mathbf{u}^2+\mathbf{v}^2+\mathbf{w}^2\right]\mathbf{R}^2\sin\boldsymbol{\varphi}\,\mathbf{d}\boldsymbol{\varphi}\mathbf{d}\boldsymbol{\theta} \quad (3)$$

Whose physical characteristics of the sphere are given by:

h : thickness of the shell
ρ : mass density of material used
(u, v, w) represents the strain components in spherical coordinates.

The expression of the potential energy U can be found in [20].

The analytical equations make it possible to calculate the values of the frequencies of the fundamental axisymmetric resonance modes, providing the natural radial frequencies of breathing and the n^{th} mode of closed spherical shells:

$$\mathbf{f_n} = \frac{\lambda_n}{2\pi R}\left[\frac{E}{\rho(1-\nu^2)}\right]^{1/2} \quad (4)$$

With **R** the radius of shell, **E** is an elastic component, **ν** define the Poisson's ratio, **n** vibrational mode rank and $\boldsymbol{\lambda_n}$ is a parameter linked at the frequency for the n^{th} mode and given by:

$$\boldsymbol{\lambda}^2{}_{\boldsymbol{n}} = \boldsymbol{\omega}^2\boldsymbol{\rho}\boldsymbol{R}^2\frac{(1-\nu^2)}{E} \quad (5)$$

The curves of Figure 3 give the solution of the first frequency components of the membrane modes using a spherical pill shape.

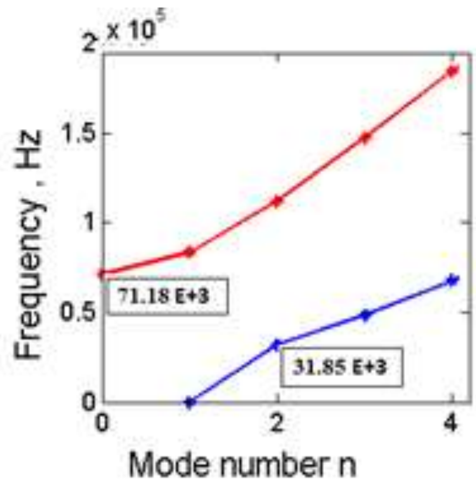

Fig. 3: Curves showing natural frequencies of tortionless motion of the sphere having a radius of R=6.7 mm, thickness h=2.6 mm, E=3300Mpa, ρ = 1190 Kg/m3, and ν = 0.39

For values of n ≥ 1, with n integer, the analytical solutions show the existence of two distinct frequency branches (lower and higher) corresponding to the membrane and bending vibrational modes. For n = 0, the structure is subjected to a resonance in spherical elongation mode (breathing) which is the fundamental mode. Results are in good agreement both in the literature such, [21], [22] and those given by a numerical approach in ANSYS modal analysis (Figure 4).

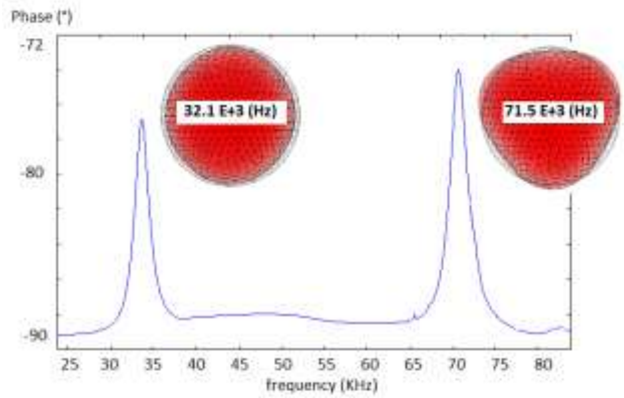

Fig. 4: Comparative results of two resonance frequencies showing the good agreement between the experimental response (impedance analysis in blue line) and the numerical simulation

3) Embedded electronics architecture

The spherical capsule is made autonomous by integrating an energy management and task scheduling device. This unit, as shown in Figure 5, is programmed to perform the following tasks:

- Control of capsule resonance in simple or coded emission mode
- Acquisition, signal processing, and data storage
- Optimal management of onboard energy
- Transmission of information in the sensor network

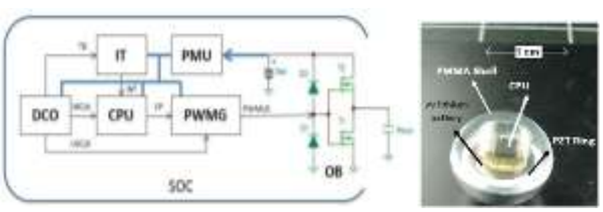

Fig. 5: Electrical architecture of the embedded unit (left) to ensure different tasks associated with the main functions of the spherical resonator sensor (right)

As shown in Figure 5, the embedded electronic chip includes a central processing unit (CPU) and subunits each of which performs a dedicated function such as the digital oscillator (DCO), a scheduler (IT), a controlled mechanical wave generator (PWMG), an energy management module (PMU), an amplifier (OB) for the output balance and a button battery (BAT). Control of the autonomy of the capsule in its entirety is managed by the energy management module (PMU) which ensures the power supply of the different elements of the chain with minimal energy consumption for maximum autonomy.

2.3 Wide-band Low-Frequency Receiver Sensor

In the design of classic ultrasonic sensors, the choice of the resonance frequency strongly determines the dimension of the vibrating electromechanical element. For an electroactive element to vibrate at resonance, its thickness must be inversely proportional to the frequency. This imposes a size restriction for the low frequencies concept, thus strongly impacting the sensor integration approach. To overcome this drawback, we proceeded in this work with an innovative approach relating to the resonance of a fine structure in concentric rings produced by laser ablation. The nature of the material and its physical characteristics were chosen to align its resonance frequency with that emitted by the vibrating capsule (Figure 6).

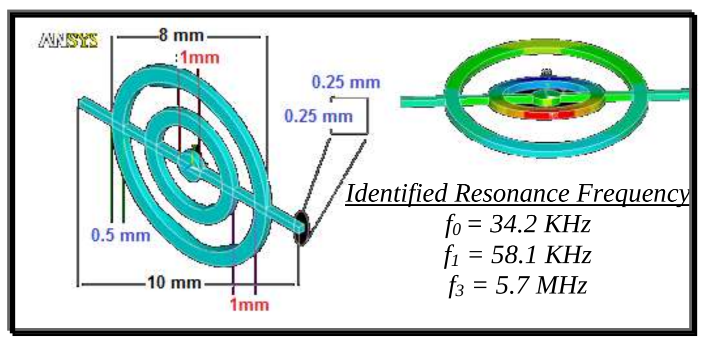

Fig. 6: Illustration showing the receiver device based on the coupling of the vibratory movement of different concentric rings. The fundamental resonance frequency of 34.2 KHz was obtained by choosing the characteristics of the vibrating element

On the theoretical level, the proposed model was the subject of a double validation both by an analytical calculation (Figure 7) using an equivalent mechanical model and a numerical simulation by numerical discrete method. The convergence of the results made it possible to evaluate the vibrational modes of the resonator and to visualize the dynamic motion (distortions). Finally, the real experimental concept was developed thanks to the strong agreement observed between the different approaches used.

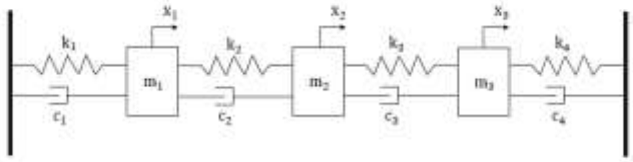

Fig. 7: Equivalent mechanical behavior by coupling the dynamic motion of an assembly of masses (m_i) split on a system of springs (k_i) and dampers (c_i)

Where k = 18.104 N/m and c = 0.5 are the physical characteristics of the elements constituting the dynamic concept (spring & dampers). And for the considered mass we give:
$m_1 = 4{,}835.10^{-6}$ Kg, $m_2 = 1{,}088.10^{-8}$ Kg & $m_3 = 1{,}813.10^{-8}$ Kg

The dynamic motion of the system satisfies the following differential equation

$$- \omega^6 + 15.107j\omega^5 + 4.1015\omega^4 - 33.1020j\omega^3 + 1.1027\omega^2 + 2.1032j\omega + 25.1036 = 0 \quad (6)$$

whose solution gives access to different frequencies f_n as: $f_0 = 35$ KHz, $f_1 = 56$ KHz and $f_2 = 5{,}25$ MHz.

2.4 Experimental Validation and Results

1) Metrological approach:

a- Evaluate Sensor stability

The application of the complete system (spherical transmitter and concentric ring receivers) in transmit/receive mode in biological tissues required validation to ensure its stability and sensitivity. Its performance has been validated in thermos-regulated water (25°C +/- 0.3°C) as a reference medium. As an example, Figure 8 shows the diagram upon reception of a 32 KHz frequency wave emitted by a spherical emitter placed in a network sensors configuration.

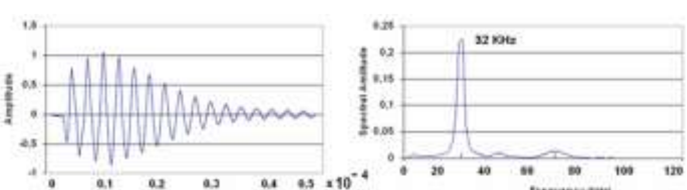

Fig. 8: Time and frequency diagram at the reception for a wave (in water as reference) emitted by a short electrical pulse exciting the capsule sensor as emitter

3 Material, Methods and Results

From a practical point of view, the speed, attenuation, and dispersion of the propagated wave were considered as the desired characteristics to estimate their variations affected by biological tissue samples from animal origin. The samples were standardized in thickness with varied properties (muscle, skin, fat, etc.). These samples were incorporated into Agar considered a coupling medium with known properties (Figure 9).

To evaluate the characteristics of the waves received by the different receptors and then to estimate information on the bio-physical state of the tissues, it is necessary to know the instantaneous position of the receptors. For this, the spatial identification of the transmitter is ensured at any time by trilateration protocol. Thus, the analysis of the wave upon reception made it possible to quantify the variation of its characteristics giving access to the desired quantities of the medium. It should be noted that a propagation speed of 1545±7m/s at 25 °C in a reference solution as reconstituted agar having controlled and perfectly known physical properties.

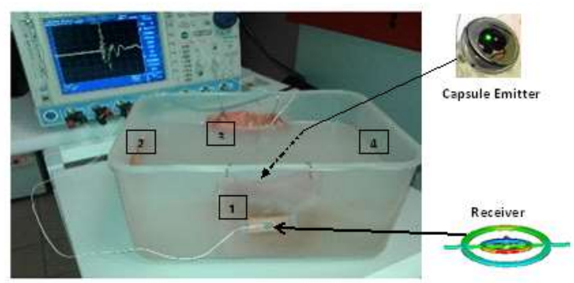

Fig. 9: Unit of measurement protocol based on a central position of the pill emitter frozen in the agar at varying distances from some receivers implanted on the different samples

The experimental configuration was conducted using different animal tissue samples, equipped with suitable receptors, and placed equidistant (10 cm) from the central position of the emitting pill.

The different receivers (R_i; i = 1, 2, 3, 4) are distributed to ensure varied reception depending on the nature and biophysical characteristics of the different samples:

1. Reception R_1 issues from 3 mm thick pure skin sample
2. Reception R_2 issued from composite 10 mm skin + muscle sample (3 mm skin & 7 mm muscle)

3. R_3 is the reception from 10 mm pure muscle sample
4. R_4 is considered as reference reception in agar solution (coupling without tissue)

The physical properties of the coupling medium (agar) and the different samples are shown in the Table 1 at the initial time t_0 of the experiment.

Table 1. Physical characteristics of different coupling medium

	Agar (0.5%)	**Skin**	**Muscle**
E	25KPa	30 MPa	480 MPa
G	148 KPa	0.58MPa	0,14 MPa
ρ (Kg/m^3)	≅ 1	1.3	1.57
ν	0.5	0.3	0.31

In this application, we have chosen to quantify the variations in the characteristics of the wave in transmission through samples at a constant temperature while considering the aging phenomenon as a variable acting as physical constraints on biological metabolism. The strong dependence of the wave propagation characteristics (speed and attenuation) on the viscoelastic properties of the medium allowed us to measure and follow over time the evolution of both the Elastic (E) and the shear modulus (G). The curves in Figure 10 show a notable decrease in the measured values over 10 days.

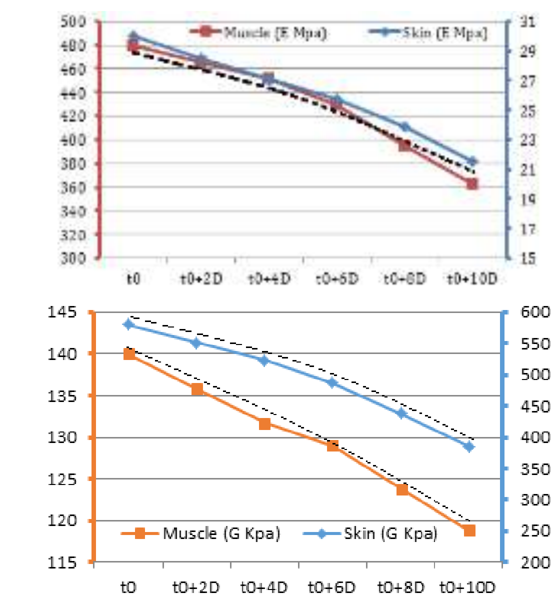

Fig. 10: Comparative results showing the agreement between the experimental measurements (solid curve) and the analytical calculation (dashed curve) of the elastic and shear modulus in various samples (agar, skin, and muscle) over a period of 10 days at a constant temperature at 25°C ±0.2°C

The measured values were continuously compared with those resulting from a matrix rigidity formalism, [23]. For the latter, results analysis shows both the local (by layer) and the global behavior of the apparent medium, and this by respect to the boundary conditions on the successive interfaces' layers. (agar-muscle-epidermis).

4 High-Frequency Endoscopic Scanning Application

For applications requiring high-frequency local scanning (4 MHz), the capsule will be equipped, by grafting, with ultrasonic transmitters/receivers distributed over six generators partially covering the overall structure (Figure 10a). By spatiotemporal sampling of the endo position of the capsule, this function will have the role of ensuring the acquisition of ultrasound once the S_{ij} sensor is in intimate contact with the internal walls of the intestines. Figure 11 shows the results of the numerical model. Indeed, by correlating the signals we can see the impact of the presence of heterogeneity affecting the walls of the intestines about a healthy environment. The coupling of the signals received, simultaneously at low and high frequencies, will provide access to the localization and evaluation of the heterogeneities of the nodules. This will help identify areas at risk or those infected by the potential development of carcinogenic tumors.

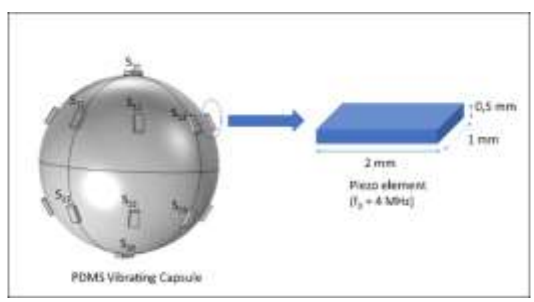

Fig. 10a: Schematic illustration of the high-frequency function of the μ-capsule showing the position of the embedded PZT sensors working on an emission/reception mode at 4 MHz of the resonance frequency. The S_{ij} ($i = 1,2,3$ & $j = 0, \ldots, 6$) represents the rank of the active sensor when it is in contact with internal tissues

Figure 11(a) shows the principle of detecting a zone of heterogeneity when the endoscopic capsule in internal circulation in the intestinal tract is in a position where one of the sensors being scanned ensures intimate contact with the internal walls. The associated numerical results show the curves relating to the emission signals (Figure 11(b)), reception signals in healthy areas (Figure 11(c)), and those that are affected by areas with detected cancerous development (Figure 11(d)).

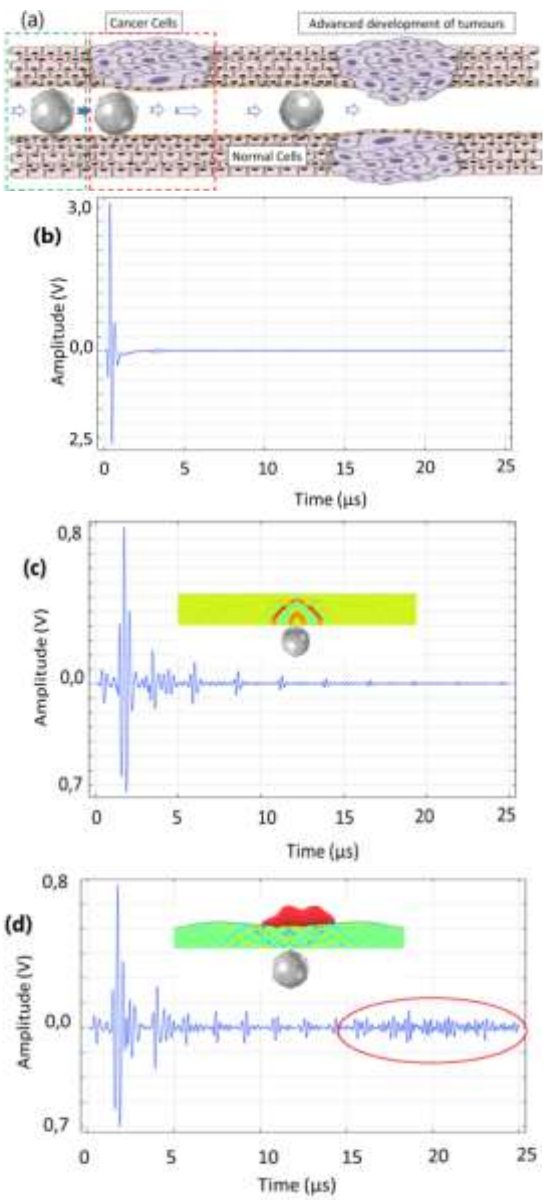

Fig. 11: (a) Synthetic image showing the passage of the capsule past different areas of potential physiopathological states of the small intestine, (b) ultrasonic signal emitted by a sensor identified Sij, (c) shape of the signal upon reception for healthy walls (green dotted square) and (d) signal disrupted by the presence of an area supposedly affected by a tumor (red dotted square)

Note that the emission of low-frequency signals from the capsule allows, the various receiver sensors distributed over the body (Figure 1), to locate the capsule inside the body by trilateration and therefore identify the pathological zone.

5 Conclusion

Measurement using an autonomous ultrasound pill capable of contributing to the physiological and/or pathophysiological diagnosis of the digestive system was the main objective of this work. To understand certain biophysical phenomena, we have attempted through this work to couple two measurement scales: a macroscopic (low-frequency system) and a microscopic (high-frequency scanning). These two scales were proposed by a unique concept based on a vibrational pill coupled to an adapted receiver for low-frequency characterization and to a surface sensor module dedicated to high-frequency endo scanning.

The analytical results of the vibrational behavior of the overall concept (transmission/reception units), consolidated by the numerical approach, enabled the design of the experimental prototype as an autonomous vibratory element for medical diagnosis. To validate our approach in a 3D space, this mechanical concept is coupled with an embedded trilateration algorithm for the localization step. Using this method, we can quantify and localize physiological changes in tissues inside the human body. However, the analysis of the curves resulting from the experimental results shows the sensitivity and dependence of the mechanical behavior of the concept on tissue aging factors over time. They also show all the critical phases in a complex evolutionary environment, knowing that there are few techniques that, under similar conditions, provide access to the desired local physical properties. We also highlighted ongoing work aimed at finalizing a high-frequency imaging module carried by this capsule. The promising results of the digital approach show the clinical potential of such a device when its coupling with computing capabilities makes it possible to record data and trigger alerts in the event of exceeding the limit of a critical value.

References:

[1] Holly S. Lay, Benjamin F. Cox, Vipin Seetohul, Christine E.M. Démoré & Sandy Cochran, "Design and Simulation of a Ring-Shaped Linear Array for Micro-ultrasound Capsule Endoscopy", *EEE Transaction on Ultrasonics, Ferroelectrics and Frequency Control*, vol.65, n°4, pp. 589-599, 2018, https://doi.org/10.1109/TUFFC.2018.2794220.

[2] Chenguang Peng, Tao Sun, Natalia Vykhodtseva, Chanikarn Power, Yong zhi Zhang, Nathan Mcdannold and TyronePorter, "Intracranial Non-thermal Ablation Mediated by *Transcranial Focused Ultrasound and Phase-Shift Nanoemulsions", Ultrasound in Medicine & Biology*, vol. 45, n°8, pp. 2104-2117, 2019, https://doi.org/10.1016/j.ultrasmedbio.2019.04.010.

[3] Hailong He, Antonios Stylogiannis, Parastoo Afshari, Tobias Wiedemann, Katja Steiger, Andreas Buehler, Christian Zakian and Vasilis Ntziachristos, "Capsule optoacoustic endoscopy for esophageal imaging", *Journal of Biophotonics*, vol. 12, n°10, pp. e201800439, 2019, https://doi.org/10.1002/jbio.201800439.

[4] Piet de Groen, "From propofol to midazolam/fentanyl to nosedation during colonoscopy: can thepropofol trend be reversed?", *Gastrointestinal endoscopy*, vol. 87, no. 6, pp. AB149, 2018, https://dx.doi.org/10.35711/aimi.v1.i1.50.

[5] Diab D., F. Lefebvre, G. Nassar, N. Smagin, Isber, S., El Omar, F. and Naja, A. "An autonomous low-power management system for energy harvesting from a miniaturized spherical piezoelectric transducer", *Review of Scientific Instruments*, 90, 075004, (2019), https://doi.org/10.1063/1.5084267.

[6] Amina Medjdoub, Fabrice Lefebvre, Nadine Saad, Saïd Soudani, Georges Nassar, "Acoustic concept based on autonomous capsule and a wideband concentering ring resonator for Pathophysiological prevention", *Artificial Intelligence in Medical Imaging (AIMI)*, 2020; 1(1): 50-64, http://dx.doi.org/10.35711/aimi.v1.i1.50.

[7] J. Wang, F. Memon, G. Touma, S. Baltsavias, J. H. Jang, C. Chang, M. F. Rasmussen, E. Olcott, R. B. Jeffrey, A. Arbabian, B. T. Khuri-Yakub, "Capsule Ultrasound Device: Characterization and Testing Results", Ultrasonics Symposium (IUS), 2017 IEEE International, Washington DC, pp. 1-4, 2017, https://doi.org/10.1109/ULTSYM.2017.8092071.

[8] F. Memon, G. Touma, J. Wang, S. Baltsavias, A. Moini, C. Chang, M. F. Rasmussen, A. Nikoozadeh, J. W. Choe, E. Olcott, R. B. Jeffrey, A. Arbabian, and B. T. Khuri-Yakub."Capsule Ultrasound Device: Further Developments," Ultrasonics Symposium (IUS), *2016 IEEE International, Tours*, pp. 1-4, 2016, https://doi.org/10.1109/ULTSYM.2016.7728851.

[9] Benjamin F. Cox, Fraser Stewart, Holly Lay, Gerard Cummins, Ian P. Newton, Marc P. Y. Desmulliez, Robert J. C. Steele, Inke Näthke, & Sandy Cochran, "Ultrasound capsule endoscopy: sounding out the future", *Annals of Translational Medıcine*, vol. 5, no. 9, pp. 201, 2017, https://doi.org/10.21037%2Fatm.2017.04.21.

[10] A.J. Walker, "A theoretical model of an ultrasonic transducer incorporating spherical resonators", *IMA Journal of Applied Mathematics*, vol. 81, pp. 1-25, 2016, https://doi.org/10.1093/imamat/hxv023.

[11] Nasedkin & A. Rybyanets, "Finite element analysis of ultrasonic spherical piezoelectric phased array with split electrodes", *2016 Joint IEEE International Symposium on the Applications of Ferroelectrics, European Conference on Application of Polar Dielectrics, and Piezoelectric Force Microscopy Workshop (ISAF/ECAPD/PFM)*, Darmstadt, Germany, https://doi.org/10.1109/ISAF.2016.7578074.

[12] James B. Mehl and Michael R. Moldover, "Precision acoustic measurements with a spherical resonator: Ar and C2H4", *The Journal of Chemical Physics*, vol. 74, 1981, pp. 4062-4077, https://doi.org/10.1063/1.441587.

[13] M. G. He, Z. G. Liu, and J. M. Yin, "Measurement of speed of sound with a spherical resonator": HCFC-22, HFC-152a, HFC-143a, and Propane, *International Journal of Thermophysics*, vol. 23, no. 6, 2002, https://doi.org/10.1023/A:1020742018220.

[14] Wilfred E. Baker, "Axisymmetric Modes of Vibration of Thin Spherical Shell", *Journal of the Acoustical Society of America*, vol. 33, 1961, pp. 1749, https://doi.org/10.1121/1.1908562.

[15] Wilkinson J. P, "Natural Frequencies of Closed Spherical Shells", *Journal of the Acoustical Society of America*, vol. 38, no. 2, 367–368, 1965, https://doi.org/10.1121/1.1909687.

[16] Kalnins A, "Effect of Bending on Vibrations of Spherical Shells", *Journal of the Acoustical Society of America*, 36, n°1, 1964, 74–81, https://doi.org/10.1121/1.2142583.

[17] Duffey, T.A and Romero, C., "Strain growth in spherical explosive chambers subjected to internal blast loading", *International Journal of Impact Engineering*, vol. 28, 2003, 967–983, doi.org/10.1016/S0734-743X(02)00169-0.

[18] Alexandru C. Moldoven, Mihnea V. Turcanu, Srinjoy Mitra, Sandy Cohran, "Ultrasound technology for capsule endoscopy", *Endorobotics (Academic Press)*, Chap 9, 2022, pp 215-240, doi.org/10.1016/B978-0-12-821750-4.00009-8.

[19] Peter A. Lewin; Keith A. Wear, "Ultrasound Exposimetry: An Essential Component of Ultrasonic Device Characterization", *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 70(2), 2023, pp 82-84, https://doi.org/10.1109/TUFFC.2023.3235506.

[20] V.C.M. De Souza, J.G. A. Croll, "An energy analysis of the free vibrations of isotropic spherical shells", *Journal of Sound and Vibration*, 73(3), 379-404, 1980.

[21] Werner Soedel, "Vibrations of shells and plates", Mechanical Engineering (A Series of Textbooks and Reference Books, 2004), https://doi.org/10.1121/1.1873932.

[22] Husson, "A perturbation theory for the acoustoelastic effect of surface waves", Journal of applied physics, vol. 57, pp. 1562, pp. 1985, https://doi.org/10.1063/1.334471.

[23] Sandrine Matta, "*Acoustic wave propagation in a multilayer composed of fluid, solid, and porous viscoelastic layers*", (UPHF - Ph.D. Thesis, 2018), https://theses.hal.science/tel-02398764.

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

- Wehbe H. carried out the analytical approach and numerical simulation of the concept
- Rabih A. focused on optimizing the choice and physical nature of used sensors
- Lefevbre F. & Nassar G. equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

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Conflict of Interest

The authors have no conflicts of interest to declare.