Electrical impedance tomography: a potential tool for intraoperative imaging of the tongue base

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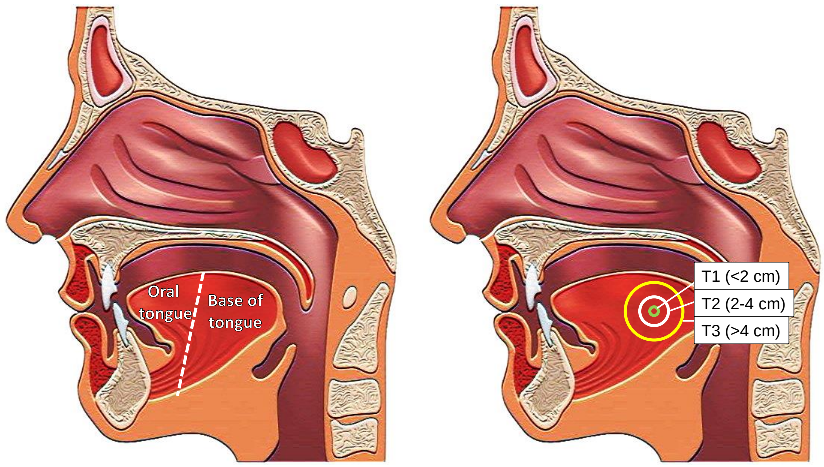
Abstract. The presence of a tumor in the tongue is a pathology that requires surgical intervention from a certain stage. This type of surgery is difficult to perform because of the limited space available around the base of the tongue for the insertion of surgical tools. During the procedure, the surgeon has to stretch and then fix the tongue firmly in order to optimize the available space and prevent tissue movement. As a result, the preoperative images of the inside of the tongue no longer give a reliable indication of the position and shape of the cancerous tissue due to the deformation of the overall tissue in the area. Thus, new images are needed during the operation, but are very difficult to obtain using conventional techniques due to the presence of surgical tools. Electrical Impedance Tomography (EIT) is an imaging technique that maps the resistivity or difference of resistivity of biological tissues from electrical signals. The small size of the electrodes makes it a potentially interesting tool to obtain intraoperative images of the inside of the tongue. In this paper, the possibility of using EIT for this purpose is investigated. A detection method is proposed, including an original configuration of the electrodes, consistent with the anatomical specificities of the tongue. The proposed method is studied in simulation and then a proof of concept is obtained experimentally on a 3D printed test tank filled with saline solution and plant fibres.

1. Introduction

The tongue is a muscle that can be divided into two parts: the oral part and the tongue base (see Figure 1.a). The oral part is visible and easily accessible, while the base of the tongue is complicated to reach during surgery. This muscle is composed of lingual tonsils which give its surface a rough and irregular aspect. A cancerous tumor can develop in the tongue base. The rate of tongue base cancer has been increasing for several decades[1]. The causes of such a cancer can be tobacco, alcohol, certain viruses (in particular the papillomavirus), exposure to certain radiations, genetic factors or certain foods. It causes discomfort when the patient swallows, difficulty of speaking, opening the mouth, and even bleeding. The most common cancer is squamous cell carcinoma,



(a) Tongue parts. (b) Tumor stages.

Figure 1. Representation of (a) the anatomy of the tongue and (b) different sizes of tumors in the base of the tongue.

which attacks the tongue directly. Other cancers can cause a tumor of the base of the tongue: salivary gland cancer, lymphoma or mucosal melanoma. The associated tumor is qualified according to its grade (the similarity rate between the healthy cells and those of the tumor) and its stage (the mass of the main tumor). The categories associated with the stage of the tumor are T0 if the doctor is unable to find a primary tumor by touch, T1 for tumors of less than 2 cm, T2 between 2 cm and 4 cm, T3 for more than 4 cm, T4a when the tumor has grown into the larynx and palate, and finally T4b when the tumor has invaded the lateral pterygoid muscles, the sides of the nasopharynx, the jawbones, and completely surrounds the carotid artery (see Figure 1.b). More details can be found in the litterature[2, 3].

To treat these cancers, three techniques can be used: resection, *i.e.* removal of the tumor (with or without reconstruction), radiotherapy and/or chemotherapy. Some studies show the benefit of surgery on long-term patient survival, especially for stage T1 and T2 tumors[4]. In general, surgery is coupled with postoperative radiotherapy to both remove the tumor and regress the cancer by irradiating the cancer cells, preventing them from multiplying.

To reach the tongue base area, the most common surgery still used today is the mandibulotomy. The operation consists of cutting a portion of the jawbone, spreading it out so that the tongue is pulled forward revealing the tongue base area to the surgeon. The surgeon can then manually palpate the area to ensure the new position of the tumor. Indeed, in spite of the precise images made by MRI or CT-scan, the tongue and its tumor are soft tissues that deform. By pulling the tongue out to perform the operation, the tumor will also stretch and its position will no longer be known precisely.

Currently, intraoperative palpation is therefore necessary to detect the contours of the tumor and thus remove it completely without removing healthy tissue. If parts of the tumor remain in the tongue, despite radiation therapy, the cancer can continue to grow; but if too much healthy tissue is removed, it can reduce the quality of life of the patient. Despite the possibility of palpation offered by mandibulotomy, this technique also damages the patient's functions and thus his quality of life and makes him much more vulnerable to postoperative infections.

Several techniques have some potential that could lead to easier and more accurate detection during surgery. Each of them has certain advantages and disadvantages. Artificial palpation[5] aims at reproducing exactly the surgeon's palpation gesture but with the help of a tool thinner than a finger, equipped with a force sensor whose position in space is known and capable of reaching the area to be operated on. However, only a 2D cartography can be obtained. Another possible imaging modality is based on the use of ultrasound[6]. Ultrasound is able to penetrate the tissue down to the surface of the tongue base and show in real time a 2D image of the obstacles encountered. Rotating the probe therefore allows the reconstruction of the area in 3D and in real time, without any harmful effect on the patient. The main drawback to date is the quality of the ultrasound image. Indeed, the ultrasound waves have to pass through the skin, a rather thick set of muscles and can collide with the jawbones when the tumours are close to them. The ultrasound is then reflected by the bone and it is impossible to visualise the tumours hidden behind it. Another imaging technique is the use of Cone Beam Computed Tomography (CBCT)[7]. It is based on the digital analysis of the absorption of a cone beam of X-rays. CBCT is less accurate (especially with respect to soft tissue contrast) than CT (computed tomography) but has the advantage of using small, mobile equipment. However, this method uses X-rays, which are dangerous for the patient in case of long exposure. In addition, it requires the presence of a CBCT device in the operating room, which is rarely the case.

In this paper, the possibility of using EIT as an intraoperative imaging tool is investigated. This method has the advantage of being relatively inexpensive, space-saving, and safe for the patient. EIT is based on the stimulation and measurement of electrical signals by means of electrodes. The most common method in EIT is to use one pair of electrodes to inject a small current of known magnitude, and then measure the resulting voltage using several other pairs of electrodes. The operation is repeated by changing the injection pair. The multitude of measurements thus obtained provides enough information to reconstruct a map of the resistivity of the studied body. EIT has shown interesting results in various biomedical applications[8] for imaging tissue resistivity. Developing an EIT-based imaging device would potentially improve the accuracy of detection compared to the surgeon's palpation, and thus decrease the amount of healthy tissue removed. On the other hand, EIT is based on the stimulation and measurement of electrical signals by means of electrodes which, if well designed, can be relatively space-saving. Mandibulectomy could then be avoided. At last, 3D reconstruction could potententially be performed using EIT with a single set of measurements, without moving the electrodes, contrarily to methods such as palpation where a movement is required.

This paper is organized as follows. The first section is devoted to the description

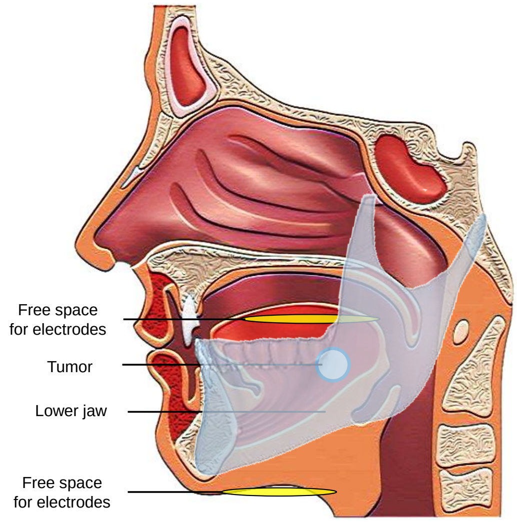


Figure 2. Illustration of mouth congestion. The lower mandible creates an insulating barrier that allows the placement of tumor-sensitive detection electrodes only on the top of the tongue and at the neck.

of the main specificities of the tongue with respect to the use of EIT. In particular, geometric and physical constraints are mentioned, and solutions are proposed. In the second section, the proposed solutions are experimentally tested on a test body representative of the tongue case. The last section concludes this work and gives the perspectives of application on biological tissues.

2. Specificities of the tongue case

2.1. Physical and geometric constraints

The mouth is composed of different elements with distinct electrical properties. In its lower part, the neck is mainly composed of fatty tissue. The tongue is composed of muscle tissue. If the patient has a tumor at the base of the tongue, it is composed of diseased tissue, the properties of which depend on the type of cancer as well as the progress of the disease[9, 10, 11]. Cancer cells are smaller in size than healthy cells. The extracellular volume, which is mostly resistive, is larger, while the cellular volume, which is mostly capacitive, is smaller. The tongue and neck tissues are surrounded by the lower mandible of the jaw, with insulating properties, as illustrated in Figure 2. This particular configuration, specific to the case of the tongue, does not allow the use of tumor-sensitive electrodes on the entire contour of the tongue. However, the neck and the top of the tongue offer the possibility to place detection electrodes. The second specificity of the tongue case lies in the difficulty of accurately modeling the domain because each patient has its own morphology.

2.2. Proposed approach: description and simulation

In this paper, the objective is to show the feasibility of detecting a tumor in the base of the tongue by EIT. To do so, different constraints must be overcome:

(i) Special configuration of the electrodes
As previously stated, the congestion of the mouth and the insulating barrier created by the lower jaw makes it difficult to use electrodes regularly distributed around the area of interest, *i.e.* around the tumor. Two planes of electrodes, at the level of the tongue and the neck, are easily accessible. The sensitivity of the measured signals to the presence of the tumor in such a configuration should be studied.

(ii) The shape of the mouth is patient-specific
The precision in the modeling of the domain, *i.e.* of the zone whose resistivity will be reconstructed, is important in order not to be a source of errors. Each patient has his own morphology, and therefore modeling the domain is not trivial. This point must also be studied.

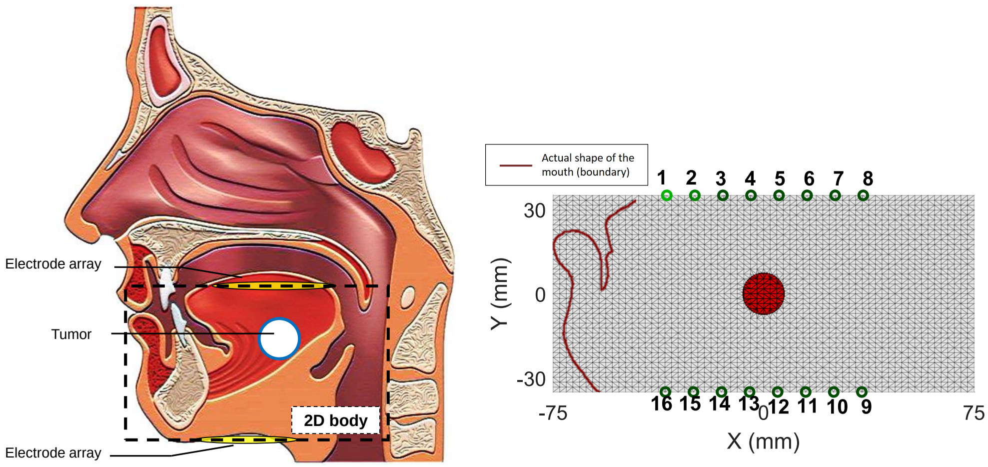
(iii) Detection method
The detection method that is often the most effective in EIT is the time difference EIT (tdEIT). It is indeed robust against model errors such as uncertainty on the position of the electrodes. As the presence of a tumor is not a temporal phenomenon, an alternative must be found.

The proposed approach is to show, first in simulation and then experimentally in the next section, the following three statements:

(i) A classical configuration of electrodes, *i.e.* regularly distributed around the area of interest, is not a necessary condition for this application case. Two sufficiently large planar arrays of electrodes, placed respectively above and below the area of interest, allow to create a sufficient sensitivity for the detection.

(ii) It is possible to generate an approximate model of the domain Ω_m that is larger than the real model Ω. This allows to compensate for the lack of knowledge of the real shape of the domain. As long as the error in the domain model is far from the area of interest (the tumor) and from the sensitivity area of the electrodes, the influence of this inaccuracy is minor or even negligible.

(iii) Cancer cells in a tumor have a different electrical frequency response than healthy cells[9, 11]. Some experimental data have been obtained for the case of the tongue[12]. It is therefore theoretically possible to use frequency difference EIT (fdEIT) to detect a tumor[13] in the tongue. The interest of fdEIT for tumor detection is well described in the literature. This method retains the advantages of differential EIT in terms of robustness against modeling errors [14] without the need for time variation. Netherless, this requires significant hardware development. Consequently, this point will not be shown in the simulations and experiments of this work, but will be in the perspectives for further work.



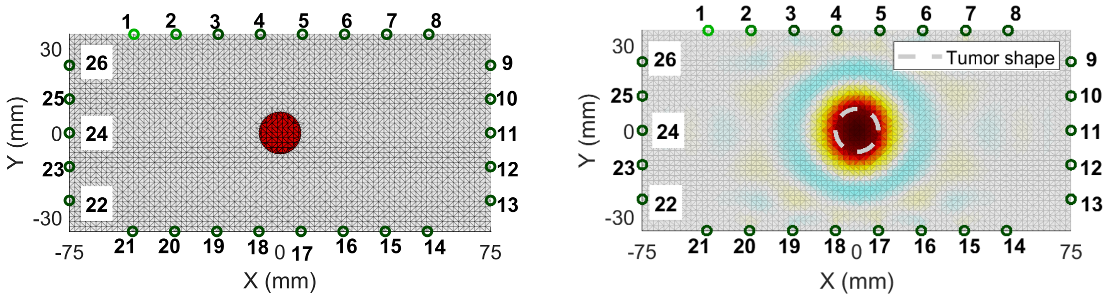
(a) Illustration.

(b) FEM representation. The tumor appears in red, and the electrodes are represented by green numbered markers.

Figure 3. 2D modeling of the tongue: (a) illustration and (b) FEM representation. A rectangle whose vertical edges are far from the electrode arrays is used as an approximate domain Ω_m. The horizontal edges cross the electrode arrays used for tumor detection.

The simulations are performed using the open source software EIDORS[15]. This software, widely used in the EIT community, exploits finite element meshes. From a known resistivity distribution within the domain, it allows to solve the so-called 'direct' problem, and thus to simulate the potentials at the level of the measuring electrodes. It also has many regularization and inversion tools, allowing to solve the so-called 'inverse' problem, *i.e.* to estimate the resistivity distribution inside the body from voltage measurements. In order to reduce the calculation time and to improve the visibility of the results, 2D simulations are performed. The electrodes are assumed to be point-like. The tongue is modeled in its mid-plane, *i.e.* the symmetry plane of the human body. The borders at the level of the chin and behind the tongue not being known with precision, the chosen model is rectangular. The height of the rectangle is chosen to be equal to a classical neck-tongue distance, *i.e.* 70 mm. The width of the rectangle is chosen to be large enough that the edges are far from the upper and lower electrode arrays. Although these are not the tissue boundaries, this modeling is still correct since the current does not noticeably flow beyond the modeled domain. The width is chosen equal to 150 mm. An illustration of the modeled area is given in Figure 3.

The possibility of reconstructing the shape of the tumor using two electrode arrays placed on the lower and upper lines of the domain is investigated. The conductivity of the medium is fixed at 0.3 S/m, and that of the tumor at 0.4 S/m. These conductivities are close to those of the tissues of the mouth. The radius of the tumor is 15 mm. As the aim is to study the feasibility of the reconstruction, we place ourselves in an ideal case: the direct problem is solved for the homogeneous case (without the tumor) and the



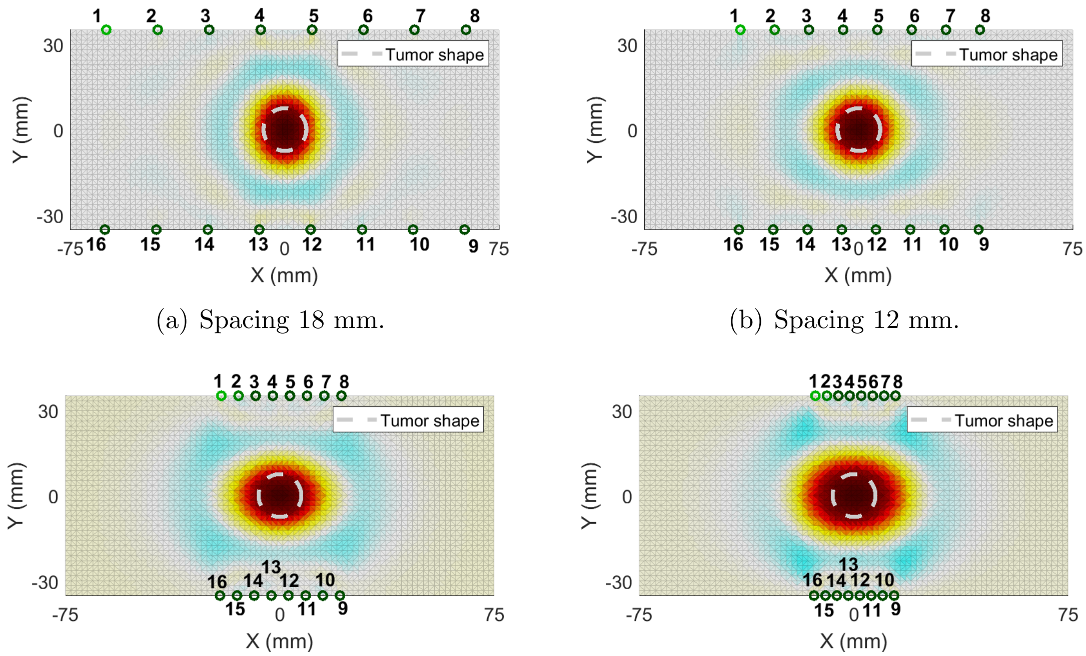
(a) FEM representation.

(b) Estimation of the resistivity.

Figure 4. Simulation of resistivity reconstruction for the most favorable case, where the electrodes are present on all boundaries: (a) FEM model and (b) result.

inhomogeneous case (with the tumor). An adjacent method is used for current injection. A *skip*-5 measurement is performed (electrodes 1-7, 2-8,...) in order to make the measurement sensitive within the domain rather than at the boundaries. The voltages thus obtained are then reused as they are (without adding measurement noise) to solve the inverse problem by a differential method, and thus attempt to reconstruct the shape of the tumor. Several simulations are performed. First, the classical case of electrodes distributed all around the domain is presented. It is used as a reference in order to estimate the quality of the results with other electrode configurations. Then, only the electrodes on the upper and lower lines of the domain are retained, an arrangement more representative of the tongue case. Finally, the inter-electrode distance is gradually reduced, so that the electrodes no longer occupy the entire horizontal boundaries. This is more representative of a real detection tool whose size does not allow electrodes to be placed on the entire tongue and neck. Finding the most efficient inversion method is not in the scope of this work. The inversion is performed with a fast algorithm, the Newton's One-step Error Reconstructor (NOSER)[16], with a hyperparameter whose value is h=10^{-3}.

For the reference case, eight electrodes are placed on the upper and lower horizontal lines, respectively, and three on each vertical border. As expected, the tumor shape is faithfully reconstructed (see Figure 4). The estimated resistivity at the borders gradually decreases due to the smoothing effect of the chosen regularization. The results when the electrodes are placed only on the horizontal borders are plotted in Figure 5. It can be seen that the reconstruction quality is similar to the ideal case as long as the electrodes cover a large area, much larger than the diameter of the tumor (Figure 5 (a) and (b)). Then the quality decreases (Figure 5 (c)), to finally become very bad with a low spacing ((Figure 5 (d)). Due to space constraints, the electrodes may not be positioned symmetrically with respect to the horizontal axis (see Figure 2). As can be seen in Figure 6, the reconstruction is still possible as long as the electrodes largely 'encompass' the tumor. This validates the first statement, which states that two parallel planar arrays of electrodes are sufficient for the detection.



(a) Spacing 18 mm. (b) Spacing 12 mm.

(c) Spacing 6 mm. (d) Spacing 4 mm.

Figure 5. Simulation of resistivity reconstruction for the case where electrodes are placed on the horizontal borders, for different spacing values: (a) 18 mm, (b) 12 mm, (c) 6 mm, and (d) 4 mm.

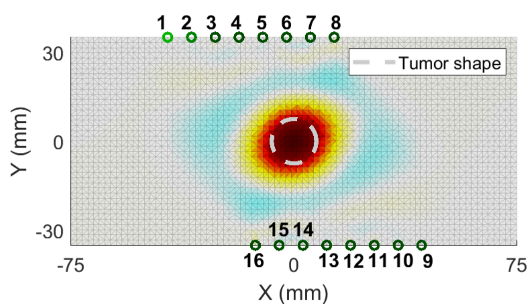
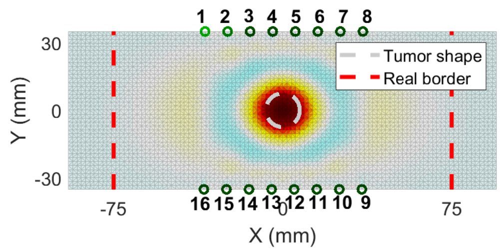
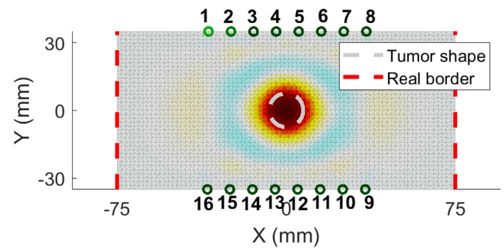


Figure 6. Resistivity reconstruction for a horizontal shift of the electrode arrays (+/- 15 mm).

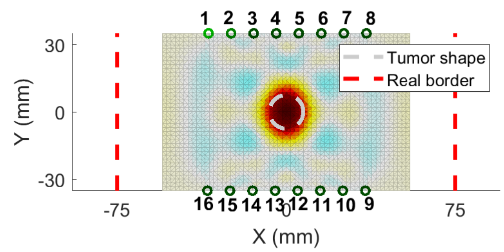
We are now interested in an error in modeling the vertical boundaries away from the electrodes. An error on the length of the rectangle along the horizontal axis allows to represent the ignorance of the real borders, *i.e.* the real shape of the chin for example (see in Figure 3). The real model Ω is assumed as shown in Figure 3.b, a rectangle of 150 mm wide and 70 mm high. The voltages for the homogeneous and inhomogeneous cases are calculated. The estimated domain for the reconstruction is intentionally wrong. Three simulations are performed, one with an estimated domain larger than the real one, another simulation with the right domain, and the last simulation with an estimated domain smaller than the real one. Results are plotted in Figure 7. We can see that



(a) Wider borders.



(b) Right borders.



(c) Smaller borders.

Figure 7. Resistivity reconstruction for different boundary models: (a) wider borders than in reality, (b) correct borders and (c) smaller borders.

the error on the modeling of the borders does not have a significant impact on the results as long as they are far from the area of interest, including the electrodes and the tumor to reconstruct. This means that the complex shape of the boundaries for the case of the tongue, for example the shape of the mouth, does not have to be known precisely, provided that the size of the domain is made large enough. In any case, if some electrodes cannot be placed far from the lateral borders, it is possible to model the domain as being wider than in reality. The area beyond the real borders will then be perceived as an insulator. This validates the second statement.

2.3. Conclusion

Simulations were performed in 2D. These simulations represent the tongue in its middle plane. It was shown that the insulating barrier formed by the lower jaw is not a lock for the use of EIT to detect a tumor in the base of the tongue. Two electrode arrays, positioned respectively above and below the tongue (at the neck), are sufficient to image the interior of the tongue and detect the tumor provided that the electrodes 'encompass' the tumor. Also, the problem of not knowing the exact shape of the borders, especially at the level of the mouth, can be circumvented by defining the domain in a simplified way, provided that it is defined until it is far from the sensitivity zone of the electrodes. Difference detection was performed in these simulations, with a view to applying fdEIT in clinical applications, fdEIT being applicable because of the difference in electrical

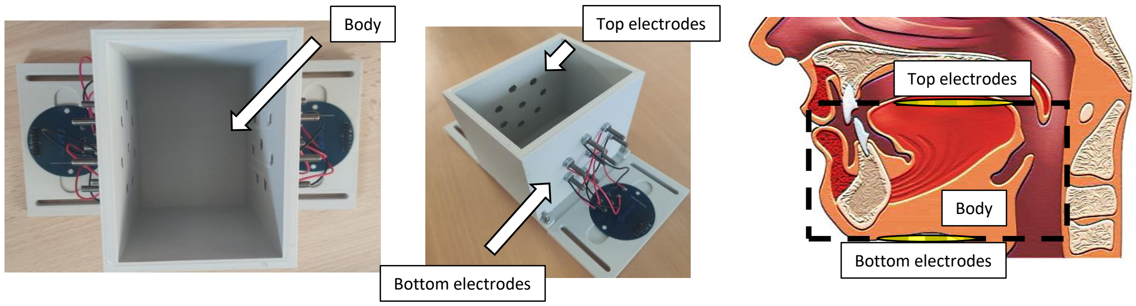


Figure 8. Simplified representation of the tongue and sensing electrodes using a 3D printed tray. Two parallel planar arrays of electrodes are placed on the walls, faithfully to the envisaged clinical configuration.

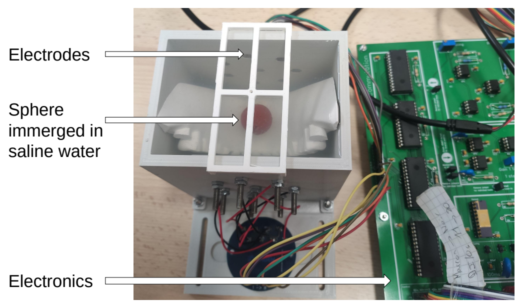


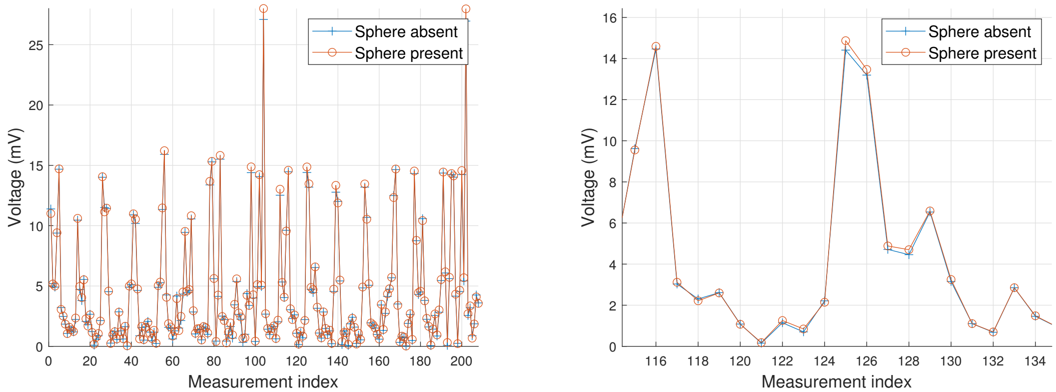
Figure 9. Experimental setup. A circular biological material is immersed in an electrolyte medium in the test tank. The tank is connected to the electronics for current injection and measurement.

properties between healthy and diseased tissues.

In the next section, the proof of concept is experimentally validated in 3D.

3. Experimental validation of the proof of concept

The body used for the 3D experimental validation is formed from a rectangular tray made by 3D printing (see Figure 8). The tank serves as a container for an electrolyte medium whose conductivity is close to that of living tissue. Its dimensions are 100x70x100 mm^3. Two parallel planar arrays of electrodes, formed from hexagonal stainless steel nuts, are placed, similarly to the clinical case under consideration. O-rings are mounted on the bolts to seal the structure, and nuts tighten the bolts. A second set of nuts holds the electrical wires that connect the electrodes to a printed circuit board, on which the connectors to the electronics are placed. Different objects are introduced in the structure in order to simulate the detection of a tumor of the base of the tongue (see in Figure 9). Inside the test tray is placed a 3D printed lower jaw, which represents the insulating barrier created by the jaw in the mouth. An electrolytic medium with a conductivity of 0.35 S/m fills the tank. This conductivity is close to that of the tongue tissue. A sphere made of dehydrated plant tissue and 20 mm in diameter (commercially available carp bait) is placed in the center of the structure. The sphere,



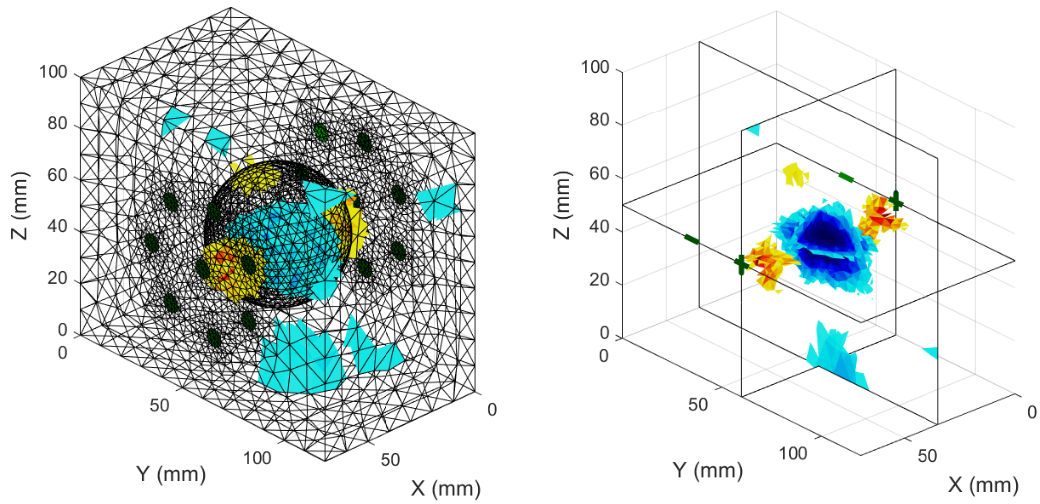
(a) Overview. (b) Zoomed-in view.

Figure 10. Plot of voltages measured with and without the sphere within the structure. (a) Full-sets and (b) Zoom on a few measurements.

which represents a tumor that we wish to detect, is held in place with a nylon wire of diameter 0.1 mm, whose influence on the measurements is assumed to be negligible. The interest of using this dehydrated sphere is on the one hand that its diameter is similar to that of a tumor that has to be surgically removed. On the other hand, the dehydrated fibers, in contact with the electrolytic medium, will absorb the liquid and thus obtain electrical properties relatively close to those of the liquid. This is representative of a tumor embedded in healthy tissue: these two bodies have distinct electrical properties, but of the same order of magnitude. The 16 electrodes are connected to an electronic device developed in the laboratory. This one allows to address the 16 electrodes. It also allows to inject an alternating current of known amplitude, and to measure the resulting voltage amplitudes by demodulating the signals.

A reconstruction by difference is adopted. Two sets of measurements must be acquired at different times: one without the sphere, and the other with the sphere representing the tumor. As previously stated, in a clinical application, the two data sets can be acquired using two different frequencies, but this out of the scope of this work. A current of amplitude 1 mA (50 kHz) is used, and the measurement strategy is 'adjacent'. The measured voltage amplitudes are plotted Figure 10. As can be seen in the figure, the measured voltag are very close in both cases, due to the fact that the sphere has absorbed liquid and thus has similar electrical properties to it.

The measured voltages are then reused in EIDORS. A FEM modeling of the domain and the boundaries is performed. The width of the domain has been voluntarily overestimated (120 mm instead of 100 mm) in order to confirm that a modeling error far from the electrodes has no significant impact. The mesh has been refined in a region of interest in the center of the domain. The NOSER algorithm is used to solve the inverse problem. The 3D resistivity reconstruction is shown in Figure 11. The presence of the sphere has been detected by the system. It is represented by a zone of lower conductivity, in blue on the figure. Small artifacts are present but do not interfere with



(a) Overview. (b) Sectional view.

Figure 11. Reconstruction of resistivity by difference using experimental voltage sets. (a) Overview with the entire mesh. (b) Sectional view in the two median planes.

the detection.

4. General conclusion and discussion

In this paper, the objective was to show the feasibility of using EIT for the intraoperative detection of tongue base tumors. The main challenges were to overcome the insulating barrier formed by the lower jaw, the difficulty to model the borders accurately, and to find an efficient detection strategy due to the lack of time variation within the structure.

It has been shown through simulations, using a model whose dimensions are typically those of the tongue, that the use of two planar arrays of electrodes placed respectively above and below the tongue is an efficient alternative to conventional EIT where the electrodes are regularly distributed around the structure. In this configuration, *i.e.* without electrodes on the sides, it is possible to model the domain in as rectangular. Although erroneous, this assumption does not have a significant impact on the results as long as the poorly modeled boundaries are far from the electrode sensitivity zone. Finally, it was shown that a difference measurement strategy (fdEIT) is compatible with the objective because of the difference in electrical properties between healthy and diseased tissue. The proposed approach was finally validated experimentally in 3D on a prototype made in 3D printing. A circular object with electrical properties very close to those of the electrolytic medium used could be faithfully reconstructed by difference using only 16 electrodes.

In further work, the acquisition of the two data sets will have to be done using two different frequencies because of the lack of time variation in the clinical case. Biological tissues will be used, with shapes closer to those of the mouth. Further characterisation of the electrical properties of the inclusion will be required to analyse the spatial resolution of a clinical device. Finally, a larger number of electrodes can be used to improve the quality of the reconstruction.

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