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INVESTIGATION BY ACOUSTIC RESONANCE OF HUMAN BODY

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Abstract. *The article aims to present a new method for investigation of malignant tissue allowing an earlier detection than that obtained with ultrasound. Usually, the signal processed by ultrasound is dependent only on local parameters of tissue on the point of investigation. Malignant nodules have some of these parameters with different values, but may be other structures with similar properties, eg., benign tissue, the situation which makes the differentiation process to be more difficult.*

When a body is irradiated with a acoustic field, the resonance phenomenon may occur if between body size, its material parameters and wavelength there are some relationships. Meanwhile, the reflected signal will be more strongly attenuated because the loss is increased. If, for some reasons, the internal structure is modified, for example, there is a nodule, then the resonance frequency changes significantly.

This article presents the results obtained by simulation when the thyroid gland was investigated by acoustic field, using finite element method. The first 16 resonant frequencies corresponding to the highest values of its eigenvalues were determined by simulation for a healthy thyroid. Malignant nodules were simulated by spheres with different radii in different spatial positions with a deviation of 10% for own material parameters. The new resonant frequencies were much more higher.

A good correspondence between the spatial positions of maximum and minimum values of acoustic pressure at the resonance frequencies was found with the areas where the arteries and veins are connected to thyroid, leading to a maximum efficiency of blood intake, at the healthy thyroid. The spatial positions of the extreme acoustic pressure were moved when the malignant nodule was inside thyroid, corresponding to a decreased efficiency of blood intake. Variations in values of resonance frequencies can be in this indicator of malignant nodules. At resonance, we achieve a much better contrast between the thyroid tumor and nearby tissue.

Another conclusion is that the amplitude of sound pressure has maximum value in the node region at certain new resonance frequencies which would allow a new method of non-invasive treatment by acoustic heating the tumor region only.

1 INTRODUCTION

Today, noncommunicable diseases represent a leading threat to human health and development. Four diseases, cardiovascular diseases, cancers, diabetes and chronic respiratory diseases, are the world's biggest killers, causing an estimated 35 million deaths each year - 60% of all deaths globally, and 77% of the disease burden in the WHO European Region [1]. Cancer is a leading cause of death worldwide: it accounted for 7.9 million deaths (around 13% of all deaths) in 2007. The number of global cancer deaths is projected to increase 45% from 2007 to 2030 (from 7.9 million to 11.5 million deaths), influenced in part by an increasing and aging global population. Cancer prevention is an essential component of all cancer control plans because about 40% of all cancer deaths can be prevented

Thyroid nodules are solid or cystic lumps formed in the thyroid gland, and can either be benign or malignant. Their prevalence increases with age and extends to more than 50% of the world's population [1]. Noninvasive medical imaging techniques such as magnetic resonance tomography (MRI), computerized tomography (CT), and ultrasonography, supervised by expert radiologists contribute to the early detection, assessment, and follow up of the nodules [2]. However, the subjectivity involved in the interpretation of the medical images made by these techniques can be regarded as their major drawback. A system that would be able to interpret these images based on explicit features could contribute to the objectification of medical diagnosis, as it could provide the experts with a second opinion, and could lead to a consequent reduction in misdiagnosis rates.

The thyroid, as a centre for metabolism maintaining, is an important endocrine gland. Its morphology could be studied from the point of view of a 3D topology. Computational modelling is an important tool for studying the structure and function of human anatomy in biomedicine. Biomedical applications use models extracted from and validated by empiric and simulation data, containing both geometric and non-geometric information. These models can be used for measurement, for simulation, and for understanding the structures and relationships that may exist among the data.

Different models for thyroid were proposed [2, 3]. They are based on the theoretical assumption and experimental evidence that symmetries in geometrical coordinates of the thyroid tissue remain invariant with respect to developmental, physiological or pathophysiological transformations occurring in the gland architecture.

From the dynamic point of view, thyroid may be investigated by means of various fields: acoustic, electromagnetic, thermal, etc. By defining a clear contour and texture with the characteristic parameters of material in relation to the neighbouring tissues, acoustic signals, investigating the structure, will be reflected by the interior walls and cumulative add, in different phase relationships, and realise stationary regimes, areas in which the field amplitude is maximal or minimum, regardless of time. These stationary regimes depend on the material parameters, shape, size and frequency of the investigating signal. The model responds with maximum amplitude at a discrete number of frequencies called the resonance frequencies [4] and the model is equivalent to an acoustic resonance cavity. The resonant cavity forms a means of storing acoustic energy, at a particular frequency within a certain bandwidth.

With the assumptions of small perturbations, undamped system, zero mean flow, and negligible temperature gradient, the acoustic pressure response of a three-dimensional acoustic cavity is governed by the linear inhomogeneous wave equation. Using the discrete system theory, the behaviour of the three-dimensional linear, acoustic cavity can be approximated by a set of linear differential equations. Starting from the

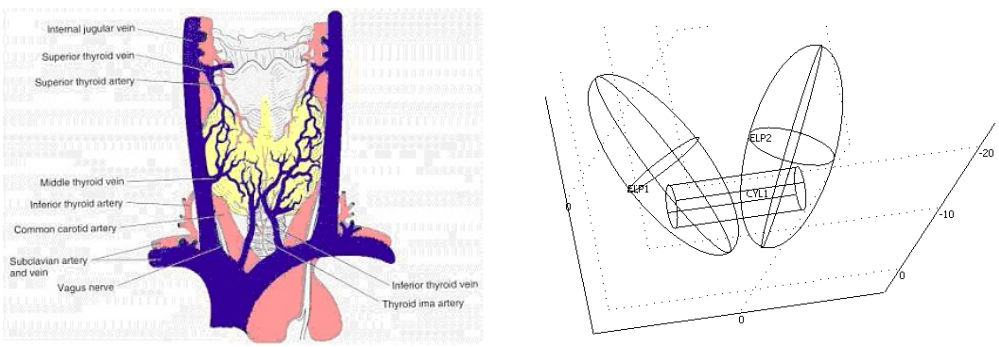
differential equations governing the propagation of the fields inside the resonant cavity the finite element technique has been developed to find natural frequencies and modes of undamped three-dimensional acoustic cavity.

It is possible to formulate and discrete a direct eigenvalue problem in terms of a set of frequency-independent real vector fields that implicitly satisfy all boundary and edge conditions of the real problem, coinciding with the exact hybrid fields at the modal cut-offs. The formal completeness of the expanding functions set is guaranteed by the fact that they constitute the eigenfunctions of the bulk wave equation. Orthonormality of the expanding set is not actually required in the discretization process.

As a result of introduction of bodies with different material parameters in the thyroid, like nodules, the internal structure of the resonance cavity will be modified and values of resonance frequencies as well. As the size of the foreign bodies is higher then frequency deviation from the initial value is greater. Depending on the direction of variation of material parameters introduced inside of thyroid gland, the new values of the resonance frequency will be higher or lower than initial values. Rhythmic tracking of frequency deviations will allow assessment of treatment efficiency of the thyroid nodule.

2 MATERIALS AND METHODS

The thyroid is one of the largest endocrine glands in the body. This gland is found in the neck inferior to (below) the thyroid cartilage (also known as the Adam's apple in men) and at approximately the same level as the cricoid cartilage, in the lower part of the front of the neck (Fig. 1.a). It lies just in front of the trachea (windpipe). The thyroid controls how quickly the body burns energy, makes proteins, and how sensitive the body should be to other hormones.



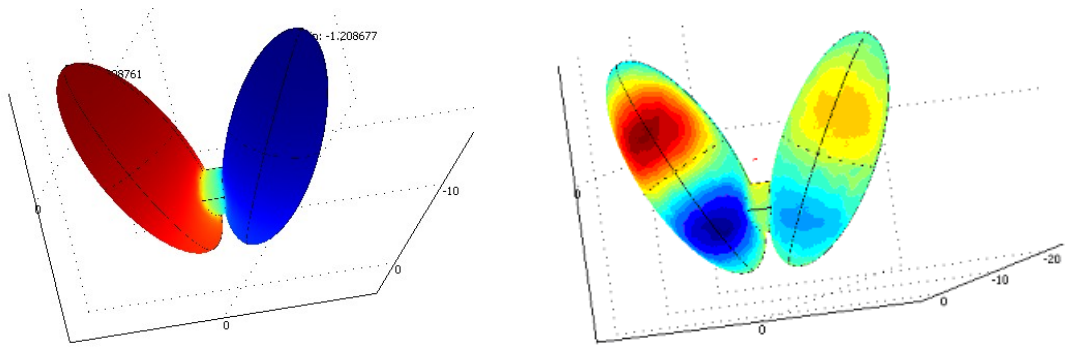
a) b)

Fig. 1 General view of thyroid gland a) and its model b)

The thyroid gland is a roughly shape of butterfly-shaped organ and is composed of two cone-like lobes or wings: lobus dexter (right lobe) and lobus sinister (left lobe), connected with a narrower band of thyroid tissue, the isthmus. We cannot usually see or feel a normal thyroid gland. The two lobes have conic-like shapes of 2/3 cases or ovoid-like shapes of 1/3 cases. The dimensions can vary; generally the lobe diameters measure, in centimetres: 5~6 (height, in the coronal plane); 2~3 (width, in the axial plane); 1~2 (depth, in the sagittal plane) [3]. In this paper the thyroid is investigated from acoustic point of view. It forms a resonant cavity storing acoustic energy, at a discrete number of frequencies called resonance frequencies. The shape of the cavity and the values of material parameters are related to the resonance frequencies that it can resonate at. The internal structure is considered to be uniformly filled with blood. Usually, it is very difficult to make a real model of the human organs. The thyroid was

modelled as two ellipsoid-like shapes connected by a cylinder, Fig. 1.b. The cylinder has radius 1 cm in sagittal plane and height is 6 cm axial plane. One ellipsoid has width in the axial plane 2.2 cm, height in the coronal plane 5 cm and depth in the sagittal plane as 2 cm. Rhythmic blood supply through arteries represents, from acoustic point of view, the sound sources, generating a sound wave. Maximum efficiency will take place when their spatial positions will coincide with the positions of extreme values of the pressure at a certain eigenfrequency, resonance frequency. The maximum value is for artery position and the minimum value corresponds to vein position.

On the Fig. 2a is shown a possible distribution of the acoustic pressure for fundamental resonance mode, where the artery will be connected at the top position of left thyroid lobe, and the vein will be connected at top position of right thyroid lobe.



a) b)

Fig. 2 The pressure distribution on fundamental resonance mode, a) and for eigenvalue λ=10.02, b)

A new resonance frequency will occur when the thyroid has a nodule and the resonance cavity symmetry will be destroyed. Extreme values of the pressure will drop if the position of blood supply and the frequency of sound wave will be keep. There are three properties that vibrate in a sound wave: the pressure, the density and the displacement of the thyroid molecules. All three properties are functions of time and space. Under normal conditions we may assume that the wavelength of the sounds wave is much longer than the mean free path (that is the averaged distance between two collisions) of the thyroid molecules. Then we may treat the thyroid as a continuous medium instead of as single molecule. For the sake of simplicity, a stationary, lossless and sourceless medium is assumed with the notation that the principle can be easily extended to other cases. With the assumptions of small perturbations, undamped system, zero mean flow, and negligible temperature gradient, the acoustic pressure response p of a three-dimensional acoustic cavity of volume V and boundary S, exited by a point monopole located inside at r_s is governed by the following linear inhomogeneous wave equation [5, 6]:

$$\nabla^2 p(r,t) - \frac{1}{c^2} p(r,t) = -\rho \dot{U} \delta(r - r_s) \tag{1}$$

Using the discrete system theory, the behavior of the three-dimensional linear, acoustic cavity can be approximated by a second order linear differential equations.By using finite difference method, in space and time; the (1) can have the following general form [7,8,9]:

$$[D]\{p\} = \lambda\{p\} \tag{2}$$

The eigenvalue problem for square matrices [D] that is the determination of nontrivial solutions of (2) is a central topic in numerical linear algebra [10]. It is

inherently nonlinear and this leads to many computational problems. Computation of the eigenvalues λ via the explicit construction of the characteristic equation:

$$\det([D]-\lambda[I])=[0] \tag{3}$$

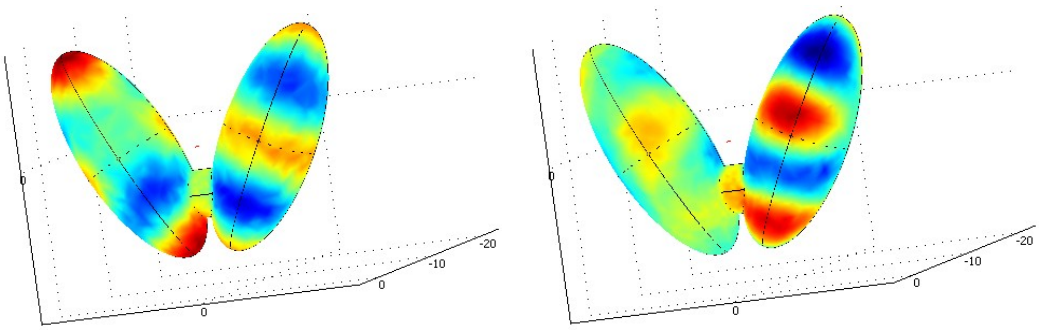
is, except for very special cases, not an option since the coefficients of the characteristic equation cannot be computed from determinant evaluations in a numerically stable way. And even if the characteristic equation could be determined accurately, then the computation of its roots, in finite precision, may be highly unstable since small perturbations in the coefficients may lead to large perturbations of the roots.

3 RESULTS

Solving numerical of equation (3) leads to *n* eigenvalues and *n* eigenvectors, where *n* is obtained from the square matrix [D] with size (*n*x*n*). For each λ_i eigenvalue an eigenfrequency can be get, because:

$$\lambda_i=-\gamma_i^2,\quad i=1....n \tag{4}$$

The eigenfrequencies correspond to resonance frequencies, and eigenvectors are connected with the acoustic pressure of a particular excitation for which the answer is proportional to excitation, the proportionality factor being the eigenvalue. A number of 16 eigenvalues have been investigated by the computer simulation using the finite element method [11].

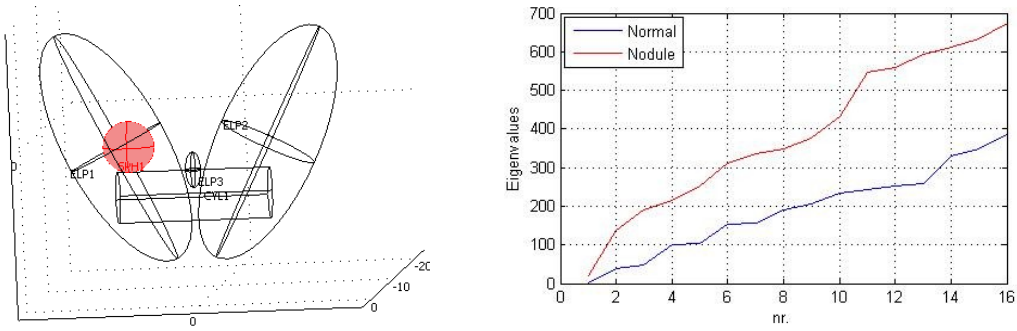


a) b)

Fig. 3 The acoustic pressure distributions for eigenvalues λ=40.16, a) and for λ=53,8, b)

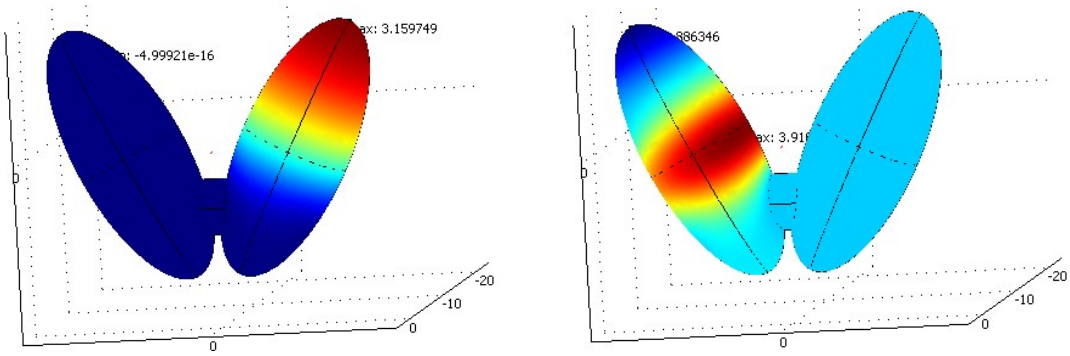
In our simulation, the blood was found to fill up thyroid and its parameters are: density ρ=1060 kg/m^3, and speed of sound v=1500m/s. The fundamental mode of vibration or resonance, with the smallest frequency, is obtained for the smallest eigenvalue. Simulated geometrical model illustrated in Fig. 1b was obtained under the acoustic pressure distribution that illustrated in Fig. 2a corresponding to eigenvalue λ_1=2.50. Note that the maximum of acoustic pressure is at the lobe peak of the thyroid, while at the second peak lobe the pressure value is is minimal. The distance between these two extremes is a half of acoustic wave. This may correspond to supply the thyroid by right superior thyroid artery and blood evacuation through the left superior thyroid vein. For the next period of acoustic wave the situation could reverse. In this way could be explained the operation of artery-vein ensemble at the superior level of the thyroid. Increased frequency of resonance, corresponding to higher modes and their higher values leads to new distributions of the acoustic pressure in thyroid. In Fig. 3 a, and b were presented situations corresponding eigenvalues λ =40.16 and 53.8. By following the spatial position of the extreme acoustic pressure, the correspondence to the arteries-veins pair positions of the lower and medium levels of the thyroid could be

observed. Pulse excitement of thyroid would correspond, by development series, the simultaneous existence of these harmonics. Following the anatomical distribution of arteries and veins, this situation would explain the normal operating of the thyroid and its effective blood supply. With almost certain, higher values used in graphical representations of Fig 3 are multiples of the fundamental resonance frequency. By inserting a nonhomogeneous material in the thyroid could lead to a disturbance of acoustic pressure distributions, as they are illustrated above. In this paper, the case of a spherical nonhomogeneous material with radius 1.2 cm was used and it is illustrated in fig. 4a. Deviation of its material parameters, as a result of anatomic changes at the neoplasic tissue, was considered to be 10%, perceivable quite difficult with a normal echograph.



a) b)

Fig. 4 Thyroid model with a cancer nodule, a) and the eigenvalues for the two thyroid models, b)



a) b)

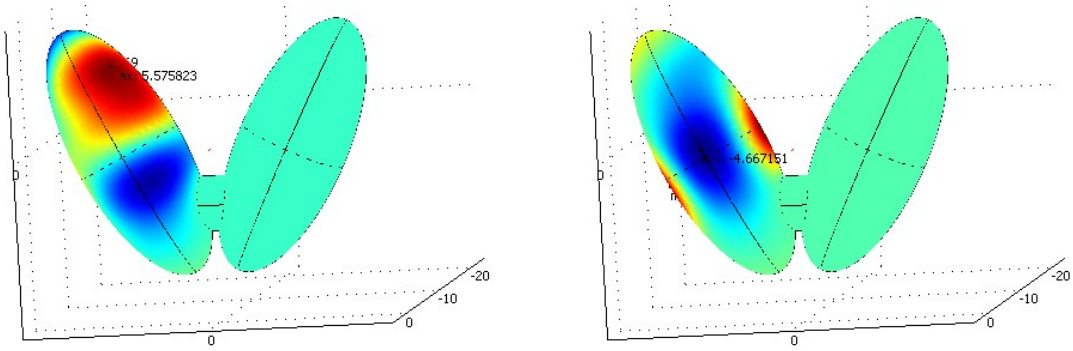
Fig. 5 The acoustic pressure distributions for eigenvalues λ=20.3, a and λ=218.6, b

Their eigenvalues are at least ten times higher and are completely different compared to the eigenvalues of the previous case. Also, the difference between fundamental frequency and first harmonica is much smaller than in the previous case, Fig. 5a. The acoustic pressure distribution in thyroid corresponding to fundamental frequency appears to be similar to the pressure distribution in thyroid without nodule, the extreme values of the acoustic pressure are placed on top of all thyroid lobes, fig. 5b, the area of low pressure is much higher. In the case of the fifth spatial harmonica, λ=218.6, the position of maximum acoustic pressure overlaps with thyroid nodule position, Fig. 5b. Interesting situations appear in Fig. 5b and Fig. 6a, for eigenvalues λ=218.6, and λ=568. In the first case, the thyroid nodule is placed in the maximum value of acoustic pressure. In the second case, the acoustic pressure is zero in nodule area. A strong asymmetry of the acoustic pressure distribution can be seen in all figures. Moreover, at the right side, where the nodule is not, the pressure has no significant variation. It could be equated with a continuous flow of blood through the thyroid and not pulse. The Fig. 6b shows the

situation where the thyroid nodule is placed between the extreme positions of the acoustic pressure.

4 CONCLUSIONS

At the thyroids with or not malign nodules, the distributions of the maximum acoustic pressures are positioned in space completely different, except the fundamental mode. By maintaining the supply-exhaust arteries-veins, the blood of the thyroid gland results in a decrease in the efficiency of the event of a thyroid nodule. As a result, this area will have a lower temperature compared with surrounding tissues.



a) b)

Fig. 6 The acoustic pressure distributions for eigenvalues λ=568, a) and λ=613 b)

At a certain resonance frequency, acoustic pressure has the maximum value only in the nodule area. Consequently, it might be possible to focus an acoustic energy only on that area. By choosing an appropriate value of power delivered by an ultrasound, could energize thyroid nodule area only, this being a new possible method of non-invasive treatment.

5 ACKNOWLEDGEMENTS

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