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# THE SONIFICATION APPROACH TO CAPTURE HARDLY DETECTABLE DETAILS IN MEDICAL IMAGES

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**Abstract** The original contribution of this paper consists in application of the sonification technique in capturing the hardly detectable details in medical images. Sonification theory translates data of the image points into acoustic signals. By reversing back, the sound samples into new images, the hidden details of the old images can be discovered. The sound is capable to discover what the eyes do not see. In contrast to sonoelastic theory which is limited to low examination frequencies imposed by the high attenuation of acoustic waves, the sonification theory is extending the range of frequencies to areas of interest. The approach is exercised on fictive images of fibrotic rat liver samples inspired from a study of effects of ginkgo biloba leaf extract against hepatic toxicity induced by methotrexate in rats.

*Key words*: Sonification; Visualization tools; Discovery defects.

## 1. INTRODUCTION

The history of sonification theory begins in 1952 when Pollack applied the information theory to evaluate auditory displays as a visualization tool [1, 2]. The first International Community for Auditory Display Conference (ICAD) organized by Kramer in 1992 generated a great interest in this multi-disciplinary theory ranging from the sciences and technology to the arts [3, 4]. Licht traces in 2007 the history of the sound art by highlighting the old art such as Sonic Youth and the contemporary art that led to provocative applications, including the works of Christian Marclay, LaMonte Young, Janet Cardiff, Rodney Graham and Laurie Anderson among many others [5].

A number of sonification approaches for visualization the structure of 3D objects assesses the capabilities of the sonification strategies [6, 7]. The nano-guitar built by Cornell University physicists from the crystalline silicon no larger than a single human blood cell, invites the bacteria inside a person to play and thus to be easily detected and tracked with a stethoscope [8]. The quantum whistle is a nano-scale sound which is able to discover oscillations in superfluid gases that are predicted by quantum theory [9].

The sonification theory allows new insights into some diseases such as the Alzheimers's dementia [10] and therapies in body movements such as walking, turning, rising arms or legs [11]. The feasibility of the sonification technique is useful to build a low-cost virtual reality environment with an increased degree of realism for driving simulators [12, 13] and a high fidelity of a 3D normal vibro-contact problem with friction [14]. For a more complete discussion of the benefits of sonification [15-21].

The sonification theory is used, in this paper, to explore the images of tissues with hardly detectable details by applying the sonification operator to bridge between the digital data and the

sound signals. By applying an inverse algorithm, new representations of images allow a better visualization of the explored tissue [22, 23]. The approach is exercised on fictive images of fibrotic rat liver samples inspired from a study of effects of ginkgo biloba leaf extract against hepatic toxicity induced by methotrexate in rats.

The paper is organized as follows: Section 2 is devoted to sonification theory. A description of the sonification parametric mapping is presented. In Section 3, the results of capturing fictive images of a damaged rat liver, are presented. The samples are inspired by a study of the effects of Ginkgo biloba leaf extract against hepatic toxicity induced by methotrexate in rats [24, 25]. The liver involves damages between 10 and 50mμ on a microscopic scale. The conclusions are drawn in Section 4.

## 2. PROBLEM FORMULATION

A 3D image $B$ of a tissue is a set of digital values called pixels located in a bounded volume $\Omega_1$ of surface $\Gamma$ embedded in Euclidean space $E^3$. A Cartesian coordinates $X_K$, $K=1,2,3$ is taken as a reference frame at time $t=0$, to locate a particle $P$ in $\Omega_1$. The set of pixels $B$ may be subjected to external loads defined as a force vector $F(t)$ written as the sum of the excitation harmonic forces $F_p(t)$ and the acoustic forces $F_s(t)$ which transform the dataset of $B$ into sound signals. The set of pixels $B$ may occupy at a later time $t$ a new configuration of pixels noted by $b \in E^3$ with position vector of Cartesian coordinates $x_k$, $k=1,2,3$.

The response of $B$ to the force vector $F$ is a new set of pixels $b$ defined by the motion of a point $P \in B$ at time $t$ is described by

$$x_k = x_k(X_1, X_2, X_3, t). \tag{1}$$

The response of $B$ is written in terms of the complex mobility matrix $\Sigma(\omega, \omega_j, \phi_j, \eta_j)$, $j=1,2,...,M$ as [26]

$$v = \Sigma F. \tag{2}$$

The mobility matrix depends on the new configuration $b$ of the body and can be written as [27]

$$\Sigma = \mathrm{i}\omega\left(\sum_{j=1}^{\infty}\frac{\phi_j\phi_j^T}{\omega_j^2-\omega^2+\mathrm{i}\eta_j\omega_j^2}\right), \tag{3}$$

where $\omega$ is the harmonic excitation frequency, the subscript $j$ is the $j$ th mode, $\phi_j$ the mass normalized modal displacement vector, $\omega_j$ is the natural frequency, $\eta_j$ is the damping loss factor associated to the $j$ th mode. The parameters $\omega_j, \phi_j$ are correlated with the set of pixels $B$ and can be found by a FEM analysis of the structure for a given estimation of $\eta_j$.

The acoustic power radiated from a vibrating set of pixels $B$ is written as

$$W = \frac{1}{2}v^T A v, \tag{4}$$

with $v$ the velocity vector.

The positive definite Hermitian acoustic impedance matrix $A$ written in term of its $M$ eigenvalues $\Lambda = \mathrm{diag}(\lambda_1, \lambda_2, ..., \lambda_M)$ and eigenvectors $Q = [q_1, q_2, ..., q_M]$ as

$$A=\sum_{i=1}^{M}\lambda_i q_i q_i^T \ . \tag{5}$$

By substituting (2) in (4) we have

$$W=\frac{1}{2}F^T\Sigma^T(Q\Lambda Q^T)\Sigma F \ , \tag{6}$$

where the superscript $T$ refers to Hermitian transpose conjugate operation.

The mobility matrix is used in [26, 27] to minimize the total sound power radiated from a structure subjected to a harmonic excitation force.

Along this paper, the mobility matrix is used to define the sonification operator sound power.

By setting

$$\frac{\partial W}{\partial F_s}=0 \ , \tag{7}$$

we determine the forces $F_s : R^N \to R^M$ , $s=1,...,M$ , which transform the $N$ -dimensional dataset $D=\{d_1,d_2,...,d_N\}, d_i \in R^N$ of $B$ to $M$ -dimensional sound signal.

The sonification operator $\psi(D,t):\Omega_1 \times T \to \Omega_2 \times T_0$ is defined as [12, 29]

$$\psi=\frac{1}{2}F_s^T\Pi F_s \ , \tag{8}$$

where $\Omega_2$ is a bounded subset of $R^n$ representing the sound domains, of sound, $T, T_0$ are working interval of time associated to $\Omega_1$ and $\Omega_2$, respectively, and $\Pi$ is a set of basic function vector

$$\Pi=\sum_{j=1}^{M}\beta_j Q_j Q_j^T \ , \tag{9}$$

with

$$\mathrm{Q}_j=\mathrm{cn}^p(m_j, k_{1j}x_1+k_{2j}x_2+k_{3j}x_3-\omega_j t+\tilde{\phi}_j) \ , \quad j=1,2,...,M \ , \tag{10}$$

where $p$ is the finite number of degrees of freedom of the cnoidal functions, $0 \le m_j \le 1$ is the modulus of the Jacobean elliptic function, and $\beta_j$ , $j=1,2,...,n$ , are unknown parameters that are determined from an inverse technique.

The inverse sonificati $\psi^{-1}(D):\Omega_2 \times T_0 \to \Omega_1 \times T_0$ on operator is given by

$$\psi^{-1}(D)=s \ , \tag{11}$$

where $s_j(x_1,x_3,t)$ , $j=1,2,...$ , with $x_3$ the vertical coordinate is the cross-sectional slices of the new configuration of pixels $b$ .

The 2D cross-sectional slices $s_j(x_1,x_3,t)$ , $j=1,2,...$ , before and after deformation of the image $B$, can be represented as polynomial expansion [30, 31]

$$l=1,2,...,M, \tag{12}$$

$$s_l(x_1,x_3,t)=\sum_{i_1=1}^{\infty}a_{i_1l}(x_1,x_3)\Gamma_{1l}(\xi_{i_1l}(t))+\sum_{i_1=1}^{\infty}\sum_{i_2=1}^{i_1}a_{i_1i_2l}(x_1,x_3)\Gamma_{2l}(\xi_{i_1k}(t),\xi_{i_2l}(t))+$$

$$+\sum_{i_1=1}^{\infty}\sum_{i_2=1}^{i_1}\sum_{i_3=1}^{i_2}a_{i_1i_2i_3l}(x_1,x_3)\Gamma_{3l}(\xi_{i_1l}(t),\xi_{i_2l}(t),\xi_{i_3l}(t))+...$$

where $\xi_{i_1}(t),\xi_{i_2}(t),...,\xi_{i_d}(t)$ is the standard Gaussian random vectors with independent components, and $\Gamma_d(\xi_{i_1}(t),\xi_{i_2}(t),...,\xi_{i_d}(t))$ is a Hermite orthogonal polynomial of order $d_G$ given by

$$\Gamma_{d_G}(\xi)=(-1)^{d_G}\exp\left(\xi^T\xi/2\right)\frac{\partial^{d_G}}{\partial\xi_{i_1}...\xi_{i_d}}\left(\exp\left(\xi^T\xi/2\right)\right), \tag{13}$$

where $\xi=(\xi_{i_1}(t),\xi_{i_2}(t),...,\xi_{i_d}(t))$.

In practice, we use a finite number of terms, so that (12) can be approximated by retaining the first $P$ terms, respectively,

$$s_l(x_1,x_3,t)=\sum_{j=1}^{P}c_{jl}(x_1,x_3)\Psi_{jl}(\xi(t)) \quad l=1,2,...,M\ , \tag{14}$$

where $\xi$ is a vector of dimension $N$. The total number $P$ is calculated from [32]

$$P=\frac{(N+d_G)!}{N!d_G!}\ . \tag{15}$$

The unknown functions $c_{jl}(x)$, $j=1,2,...,P$, $l=1,2,...,M$, are find by a genetic algorithm.

## 3. THE PROBLEM SOLUTION

The intersection detection algorithm has to find if two points $P_1\in F_1$ and $P_2\in F_2$ are in contact.

The images chosen for sonification may exhibit abrupt changes in profile. A 3D sample of a fictive rat liver is shown in Fig. 1a, and the size of constituents are displayed in Fig. 1b, respectively.

The rat liver involves damages zones between 10 and 50 μm at the microscopic scale.

The sonification operator (8) is applied to three images of the cross-sections of the fictive rat liver at $t=0$ sec and $t=10\sec$, respectively. A genetic algorithm was applied in order to obtain comparable images to the photomicrographs reported in [24] for a rat liver with severe loss of architecture and disturbances. These images are shown in Fig. 2a and Fig. 3a, at $t=0$ and $t=10\sec$, respectively. The cross-sectional slices $s(x_1,x_3,t)$ are represented in Fig. 2b and Fig. 3b, respectively. Each spectrometer pixel is in the range 300 nm to 1000 nm, with 3.125 nm wide. A discrete inhomogeneity, such as a defect or tumour, produces a localized disturbance in the vibration pattern, forming the basis for defect detection [33-35].

The simulations of (1) show a slight tendency to instability in determining $s(x_1,x_3,t)$ after deformation at $t=10\sec$. To analyse this, the $s(x_1,x_3,t)$ are multiplied by $1+r$, $r$ being random numbers uniformly distributed in $[-\varepsilon,\varepsilon]$, with $\varepsilon=0,\ 0.01,\ 0.1$ [12]. The results show good accurate values for $s(x_1,x_3,t)$ with a maximum error of $6.7\times10^{-5}$ for $\varepsilon=0.01$, and $9.36\times10^{-4}$ for $\varepsilon=0.1$, respectively. Final cross-sectional slices $s(x_1,x_3,t)$ represented in Fig. 3c are computed for $\varepsilon=0$ .

The cross-sectional slices of the liver are built by interpolating the sound parameters furnished by $\psi$ .

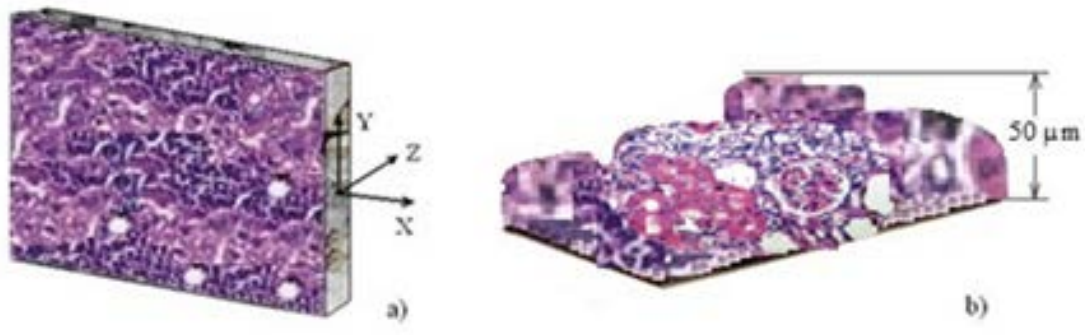


Fig. 1 a) A 3D sample of a fictive rat liver; b) The size of constituents.

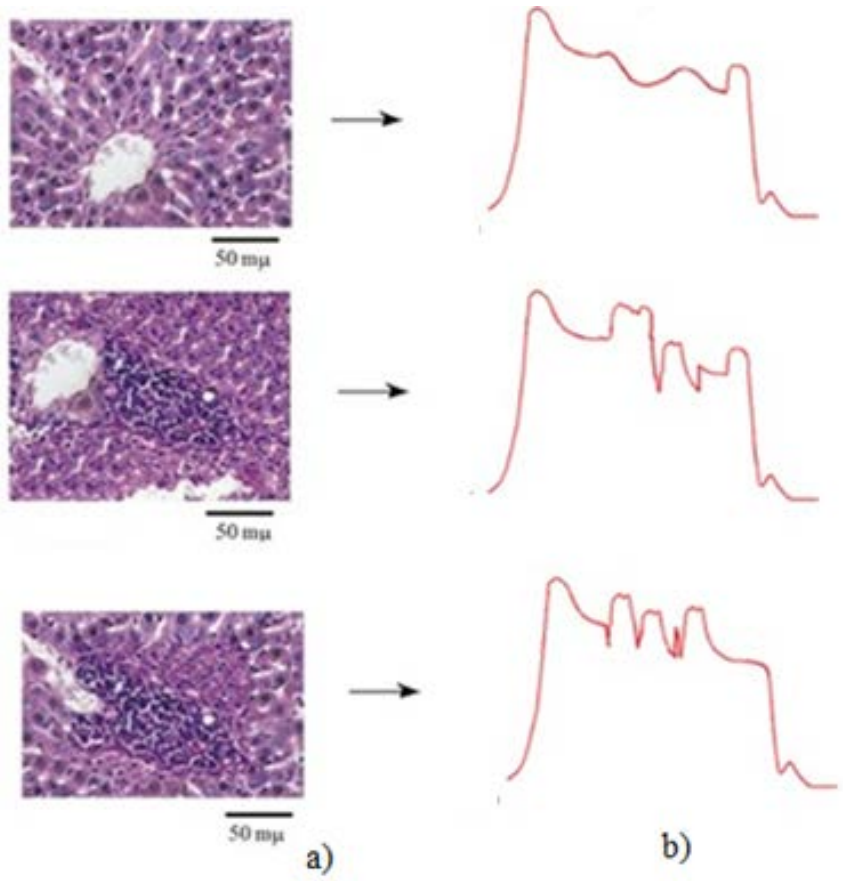


Fig. 2 a) Three images of the cross-section of a fictive sick rat liver; b) Cross-sectional slices $s(x_1, x_3, t)$ at $t = 0$ of the damaged sample.

The images shown in Fig. 2a and Fig. 3a are transformed by sonification into three samples of sounds which are reversed back by applying the inverse operator $\Psi^{-1}(D) = s$, given by (11), to new images in which we hope to find hidden details and information compared with original images.

The problem (11) is an ill-posed problem in the sense that the solution does not depend continuously on data. The solution of (11) is sought in this paper as the minimizer of the distance between the 3D image data $s$ given by (12) and the sound domain $D$ given by (8). The minimization problem is solved by using gradient methods, such as Quasi-Newton method.

The results show the efficiency of solving the ill-posed problem (11) in order to visualize final images of slices at different moments of time.

Fig. 4a shows the rat liver sample with nine sectional slices at $t = 0\text{sec}$, and Fig. 4b visualizes images of slices at $t = 0\text{sec}$. Fig. 5 displays the images of slices at $t = 10\text{sec}$. By comparing these images with those from Fig. 4b at $t = 0$, we observe small differences highlighted in yellow in the last 6 images.

The next step is to show the efficiency of the sonification procedure and to verify the correctness of the results. For this, we compare our results with other results in the literature obtained by other methods or by experiments.

We consider the work of Salameh [25] that study the detection of nonalcoholic steatohepatitis in the fatty rat livers by magnetic resonance (MR). This study is useful in the early detection of fibrosis in the at livers.

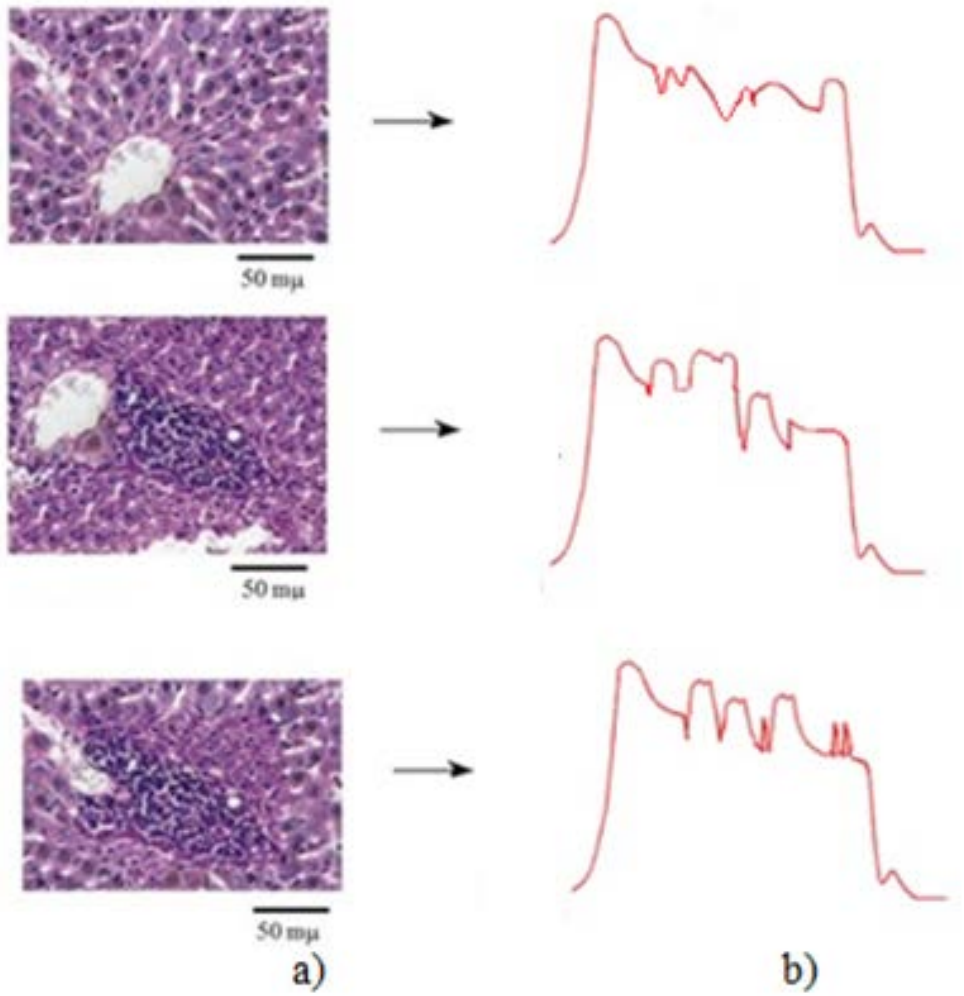


Fig. 3 a) Three images of the cross-section of a fictive sick rat liver; b) The cross-sectional slices $s(x_1, x_3, t)$ at $t = 10\text{sec}$ of the damaged sample.

Fig. 6a shows the MR image of such a liver rat. Fig. 6b displays the simulation results of slices of this liver sample obtained by sonification technique.

Liver sections show severe loss of architecture, disturbances of the hepatocytes and strong hepatocellular, in good agreement with [25]. With red are indicated new disturbances detected by sonification that are not present in above mentioned paper.

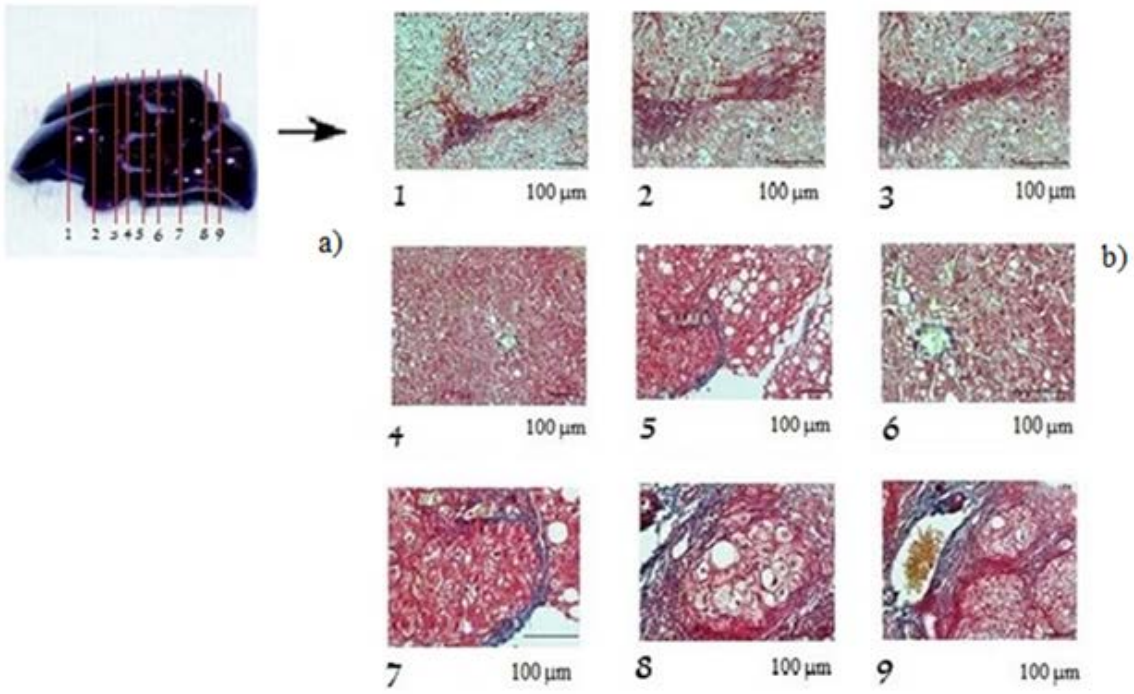


Fig. 4 a) The rat liver sample with nine sectional slices at $t = 0\,\text{sec}$ ; b) Cross-sectional slices of the sample at $t = 0\,\text{sec}$ .

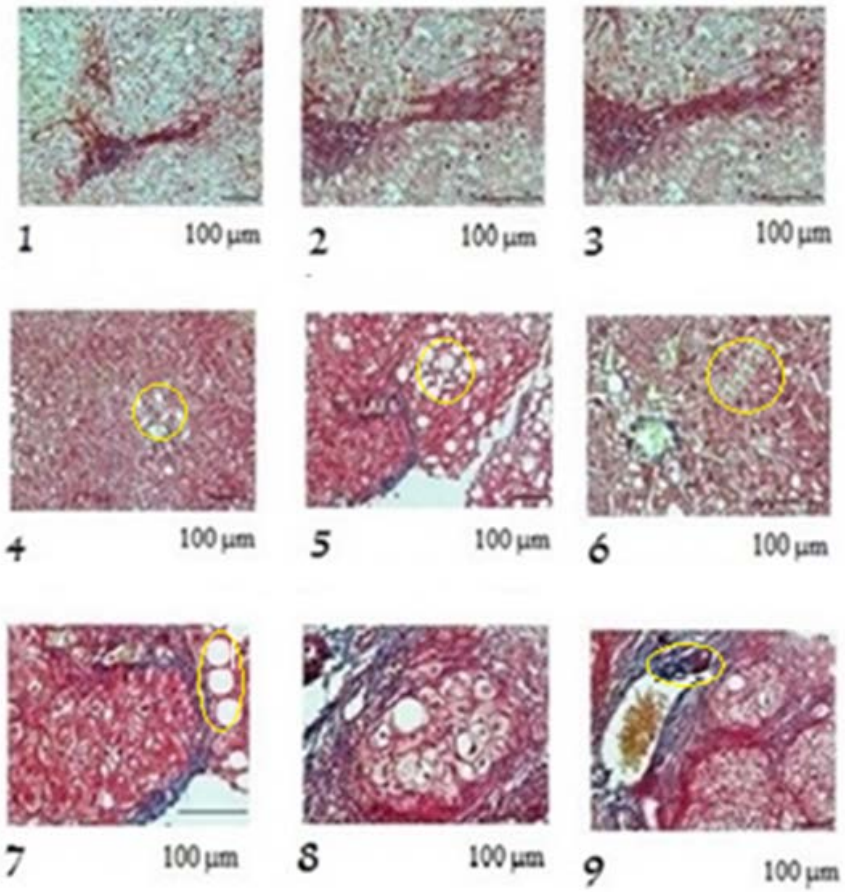


Fig. 5. Cross-sectional slices of the sample at $t = 10\,\text{sec}$ . Differences with images of Fig. 4b are highlighted in yellow.

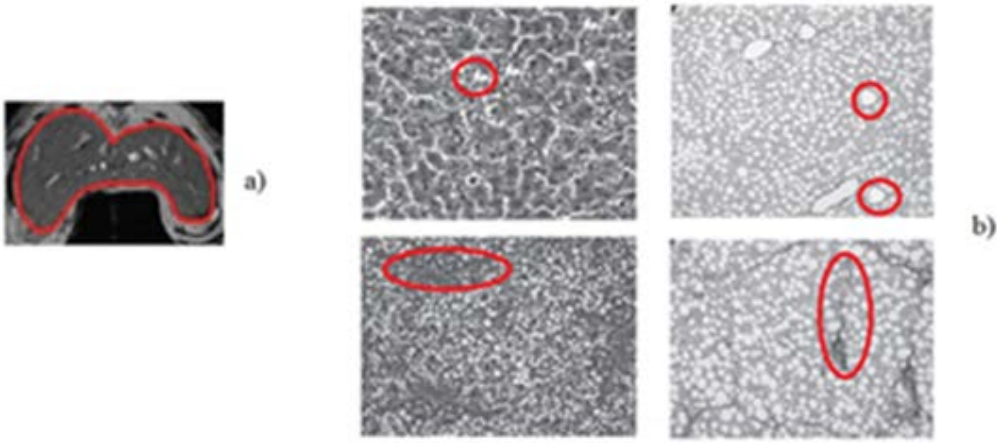


Fig. 6 a). The MR image of a liver rat; b) The cross-sectional slices of this sample obtained by sonification technique.

## 4. CONCLUSIONS

The numerical simulations of the spatial motions described in this paper have the property that all poi the base and platform, respectively. These results are of interest for control, on-line simulation and p In this paper, we consider the problem of capturing hardly detectable details in the images of anatomic tissues by mapping the imaging data into acoustic signals, using the sonification operator.

The sonification operator is converting the digital data field into sounds, using a set of basic functions defined as series of cnoidal vibrations. By inverting the samples of sounds by the inverse sonification operator, the final images are obtained and examined to find hidden details and information compared to the original photos. The approach is exercised on fictive images of fibrotic rat liver samples inspired from a study of effects of ginkgo biloba leaf extract against hepatic toxicity induced by methotrexate in rats.

The inverse sonification problem is an ill-posed problem in the sense that the solution does not depend continuously on data. The solution of this problem is found as the minimizer of the distance between the set of images data $s$ and the corresponding sound domain. The minimization problem is solved by gradient methods, such as Quasi-Newton method. The errors that occur in solving of this inverse problem are acceptable (maximum error $6.7\times10^{-5}$).

To show the efficiency of the sonification procedure and to verify the correctness of the results, the comparison of results with other results in the literature is performed. The work of Salameh [25] with the detection of non-alcoholic steatohepatitis in the fatty rat livers by magnetic resonance (MR) is chosen for this comparison. The results are goods showing the potential and flexibility of the proposed method.

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