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Original articles

Analysis of the movement of food bolus: a comparison between a healthy esophagus and a chagasic megaesophagus

Análise do deslocamento do bolo alimentar: comparação entre o esôfago saudável e modelo de megaesôfago chagásico

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Conflict of interest: non-existent

ABSTRACT

Objective: to study the dynamics of the human esophagus behavior when affected by Chagas disease.

Methods: a mass-spring-damper model was proposed to model the food through the esophagus during peristaltic action. After that, parameters were recalculated to simulate a chagasic megaesophagus.

Results: the velocity and displacement curves from both models were analyzed and the dynamic differences between the healthy organ and the ill one, identified. According to the results obtained, the food displacement in a chagasic megaesophagus type II (3 centimeters dilated) is just 11.84% of the displacement in a healthy esophagus.

Conclusion: Chagas disease generates a velocity close to zero and a high dampering in the downwards curve of the bolus whose displacement cannot return to its initial state, due to aperistalses, which proves the food bolus retention. With the introduction of the proposed organic control system, an approximation of the curves that remained with dynamic behavior close to the model of the healthy organ was obtained, minimizing the retention of the food.

Keywords: Esophageal Achalasia; Chagas Disease; Esophagus

RESUMO

Objetivo: estudar a dinâmica do comportamento do esôfago humano quando afetado por doença de Chagas e propor um controlador orgânico para auxiliar no aperistaltismo do órgão.

Métodos: um modelo de massa, mola e amortecedor foi proposto para modelar o deslocamento do bolo alimentar no esôfago durante a ação peristáltica. Foram utilizados parâmetros da literatura para simular o megaesôfago chagásico e o saudável.

Resultados: foram analisadas as curvas de velocidade e deslocamento de ambos os modelos e identificou-se as diferenças dinâmicas entre o órgão saudável e um doente. O deslocamento de alimentos em um tipo de Chagas megaesófago II (3 centímetros de dilatação) é apenas 11,84% do deslocamento num esófago saudável.

Conclusão: a doença de chagas gera uma velocidade próxima de zero e um alto amortecimento na curva de descida do alimento que devido ao peristaltismo o deslocamento que não pode retornar ao seu estado inicial, o que comprova a retenção do bolo alimentar. Com o sistema de controle orgânico proposto obteve-se uma aproximação das curvas a um comportamento dinâmico próximo do modelo do órgão saudável, minimizando a retenção do alimento.

Descritores: Acalasia Esofágica; Doença de Chagas; Esôfago

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INTRODUCTION

The movement of the bolus in the esophagus is a result of the neural stimulations and the contraction responses its muscular wall, generating peristaltic forces that are responsible for the food bolus transport to the end of the organ[1]. The esophageal Chagas disease is characterized by inflammatory lesions in the enteric nervous system, associated with a drastic reduction in the number of active nerves. As a result of the intrinsic denervation, there is a motor incoordination, a retention of the food bolus transport, a muscular hypertrophy and, finally, an esophageal dilatation, leading to the formation of the chagasic megaesophagus[2-4]. The main symptoms are related to oropharyngeal swallowing, dysphagia, food regurgitation, heartburn and chest pain, and some may present with weight loss, halitosis and breathing difficulty[5-7].

Studies on the gastrointestinal aspects of Chagas disease are important for allowing the development of a natural model to comprehend the consequences of the destruction of the enteric nervous system in humans[8]. In Brazil, it is estimated that there are between 8 million and 10 million people with Chagas disease, which is among the four main endemic diseases in the country. Annual global expenditures are roughly US$ 627,000. "There is no effective treatment for this disease. Drugs available for the treatment merely kill extracellular parasites and the nerve damage they cause is irreversible"[9].

The megaesophagus can be classified in four different grades, according to the transverse diameter of the esophagus image and the duration of the stasis (stoppage of the normal flow of a bodily fluid)[6,10].

- Grade I: Moderate dilatation, up to 4 cm of transverse diameter. Slight stasis at 5 minutes;
- Grade II: Dilatation up to 7 cm of transverse diameter. Stasis at 30 minutes;
- Grade III: Dilatation up to 10 cm of transverse diameter, sigmoid elongation of the esophagus (dolicomegaesophagus). Stasis detected after 30 minutes. Food residue caused by stasis, giving the contrast image;
- Grade IV: Dilatation greater than 10 cm of transverse diameter. Non-contrast image, presenting a dilatation occurred only by the food residue stopped in the esophagus.

The megaesophagus is a disease in which the functional alterations are permanent and progressive. There is still no definitive treatment for it, and therapeutic alternatives only relieve symptoms. Surgical treatment, indicated for not advanced cases, do not correct the functional disorder of the organ and the main symptoms are recurrent[11].

In most cases, the modelling of a biological system permits the study of the phenomena of a complex system by means of a mathematical representation. The mechanical behavior of the human esophagus, for example, can be considered as a system. In this system, the input is the force generated by changes in pressure between the lower pharynx and the superior esophageal sphincter stimulated by the passage of food. The output, on the other hand, would be a severe system exit or motility of the food bolus through the esophagus to the stomach. These two quantities can be defined as the main characteristics of the system and can also be measured in real time. Other features can also be analyzed and included as other variables in the model[12]. There are two types of systems modelling: "*input-output and state-space representation*"[13]. This paper has opted for the phenomenological model (i.e., based on Physics Laws) and for the state-space representation, so that the output is the function of these state variables.

When proposing a model for a biological system, it is used equivalents analog to other system, as it is done in engineering. Thus, it is possible to alter its dynamics by means of feedback controls. In this way, it is possible to propose alterations in complex systems, such as the process of passage of the food bolus through the esophagus, in order to improve its functions even in the occurrence of noises, fluctuations or unpredictable changes.

For these biocomplex systems, as in the case of esophageal treatment, it is necessary to use a control architecture in which the action is applied in parallel, that is, the input and output data are working in normal time. The concept of Organic Control seeks to satisfy this reality, with objectives of adjustment and reinforcement of the alteration of the plant dynamics of a biological system, such as the passage of the food bolus through the esophagus. This intervention occurs due to biomedical reasons, being presented as a contribution of biomedical engineering for the treatment of a specific disease. Thus, it is proposed in this work the design of an organic controller, responsible for propagating artificial peristaltic waves by the diseased organ, allowing the dynamic activities to be restored or reinforced, so that the food can be moved to the stomach.

Hence, an intervention of an organic controller aims at achieving a standard performance of the esophagus, by using biomaterial (latex) and / or by sensing[14]. The organic controller to be designed acts in parallel to the plant and receives the same input. Its output is added to the output of the system, and can be monitored via sensing, which will allow automation and better corrections of the output signal.

METHODS

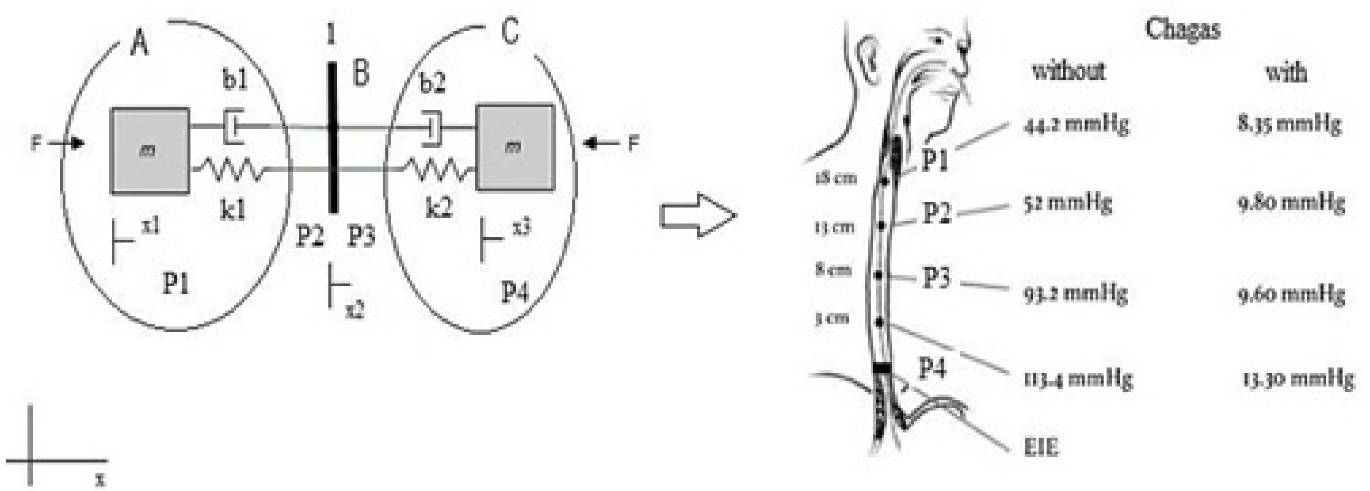
Patients with Chagas disease have alterations in esophageal motility, characterized by I) lower contraction amplitude; II) higher contractions velocity in the middle part of the esophagus and III) lower pressure of the lower sphincter. Based on these three parameters, a bioinspired organic control system has been proposed. This control performance takes effect via an *esophageal blanket*, derived from natural latex (biotechnological latex), whose purpose is to adjust these parameters expecting a contribution to the treatment of the chagasic esophagus. The development of a mathematical model that represents the functioning of the human esophagus stricken by Chagas disease is very complex (typical of physiological systems).

Building the chagasic and non-chagasic Esophagus model

The proposal of the mathematical model is to represent the referred physiological system with a mass-spring-damper mechanical model, as shown in Figure 1, which (a) shows the entire extension of the esophagus and what each point (P1 through P4) represents. The distribution of pressure values at points P1, P2, P3 and P4 in the chagasic esophagus and in the non-chagasic esophagus is presented in (b).

Figure 1

In Figure 1 (a), the first mass-spring-damper set, observed from left to right, is supposed to model the reduction of the esophageal amplitude. The left side of the model represents the upper part of the esophagus,



(a) (b)

Figure 1 – Mass-spring system diagram equivalent to the esophagus – 2015. Source: Adapted[15].

and the right side of the model represents its lower part. The external forces F_1 and F_2 represent the peristaltic contraction, considering that a force on the left side F_2 is generally null. Force F_1 is zero at rest, but it must be a pulse during the passage of the bolus. The masses (m) represent the mass of the walls of the esophagus (which are very small) and support the storage of kinetic energy. The spring (k_1) and damper (b_1) elements are able to model the reduction of amplitude and velocity in region 2, and the spring (k_2) and damper (b_2) elements are, in region 3, the pressure loss of the lower sphincter.

In fact, the loss of energy in the damping elements will imply in this reduction of the pressure. The food bolus, represented by a bar (1), does not move by gravity in this study, and the point where the highest velocity of the contractions is measured is in the middle part of the esophagus (represented by the speed of the bar). The external force F_1 and F_2 are forces acting on the wall of the esophagus at distinct points – the first being in the upper sphincter and the second in the lower sphincter. In the literature, it is stated that the average time for the peristaltic wave to reach the end of the standard human esophagus (a man, 1.60 m, normal BMI and normal esophagus) is 7 seconds[15,16].

The values for the spring (k) and the damper (b) constants are calculated from the different pressure values on the esophageal extension and diameter and the peristaltic wave velocity. Through the manometry studies described in the literature[1-4,8], it was possible to obtain pressure values in the esophagus during peristalsis, due to the ingestion of 5 ml of water. In Figure 1, pressure values are presented at four study sites in the esophagus. Region A is the one that reflects the reduction of the amplitude to chagasic esophagus compared to healthy esophagus; region B represents the increase of the velocity of the bolus in the middle part of the esophagus; and region C represents the decrease of sphincter pressure, which reflects in the emptying of the esophagus. Note that the image shows the pressure values for chagasic and non-chagasic cases.

For the calculation of the constants of the spring (ki) and the damper (bi), equation (1) is adopted, where i = 1, 2, 3, 4 is the pressure index in the indicated region[1,8].

$$\mathrm{ki} = \frac{\text{pressão}\left[{}^{\mathrm{N}}/_{\mathrm{m}^2}\right] \times \text{área}\ [\mathrm{m}^2]}{\text{posição}\ [\mathrm{m}]} \qquad \mathrm{bi} = \frac{\text{pressão}\left[{}^{\mathrm{N}}/_{\mathrm{m}^2}\right] \times \text{área}\ [\mathrm{m}^2]}{\text{velocidade}\left[{}^{\mathrm{m}}/_{\mathrm{s}}\right]} \quad (1)$$

A) Parameters of the healthy esophagus system

The values of 2 cm/s for peristaltic wave velocity and 3 cm for esophageal diameter were used to calculate the spring and damper constants[1,8]. Computed tomography (CT) shows that the esophageal wall of a normal esophagus has an mean thickness of 0.35 cm, 28 cm in length and a radius of 3.0 cm[3,4]. Thus, it is possible to obtain the approximate volume of a hollow cylinder, which, for the case being studied, has adopted an average volume value (V) = 173.95cm^3. By the average pressure obtained from the literature on the wall of the normal esophagus, we have a wall esophageal density calculated in the classical way, where the pressure is determined by the product of density ρ, gravity g, and height h, where P is the mean pressure of the normal esophagus wall and the esophageal density of the normal esophagus is given in g/cm^3. For g = 980 cm/s^2 and P = 102.9 gf/cm^2 (75.7 mmHg), it is found that ρ = 3.75 10^{-3} g/cm^3. The mass (m) is given by m = 0.65 g for non-chagasic esophagus[4].

B) Parameters of the Chagasic megaesophagus system

The pressure and diameter values of the megaesophagus were obtained in [9]. This manometric study was also evaluated in four 5 cm spaced points along the extension of the organ affected by Chagas disease, where the value of the internal diameter of the organ is 6.0 cm and "M" in the index indicates the presence of a chagasic megaesophagus. The esophageal wall has a mean thickness of 0.5 cm, with a length of 28 cm, a radius of 6 cm and Volume (V) = 505.79 cm^3, using the same procedure for chagasic megaesophagus, by computed tomography (CT). Where P is the mean pressure of the wall of the chagasic esophagus; ρ is the esophageal wall density given in g/cm^3, g = 980 cm/s^2, and P = 13.9 gf/cm^2, thus ρ = 5.06 .10^{-4}g/cm^3, so the mass (m) is m = 0.25g for chagasic esophagus. The following additional hypotheses were considered: a) the wall of the esophagus is assumed to be uniform along the length; B) the calculated masses are considered uniform along the length of the esophagus – whether or not chagasic; C) the movement analyzed is translational in x towards the esophagus – with no deflections or vibrations; D) the influence of surrounding organs is neglected. In order to obtain the mathematical model, *Bond Graph* and Movements Equations[12,14] have been adopted in studies carried out by the research group.

Building the Mathematical Model

The inputs of the system are external forces called F, which may vary in other studies. By using the equilibrium equations of the system (balance of forces) and applying the constitutive relations, the following equations of motion for the mechanical translational system are obtained, as shown in Figure 1 (a). This model was obtained by applying the Newtonian free body diagram method, which provides the mathematical relationship of the system. Then, it is given the mathematical model I, which represents the proposed complete esophagus.

$$m\ddot{x}_1 = -b_1(\dot{x}_1 - \dot{x}_2) - k_1(x_1 - x_2) + F \tag{2}$$

$$k_1(x_1 - x_2) - k_2(x_2 - x_3) + b_1(\dot{x}_1 - \dot{x}_2) + b_2(\dot{x}_2 - \dot{x}_3) = 0 \tag{3}$$

$$m\ddot{x}_3 = b_1(\dot{x}_2 - \dot{x}_3) + b_2(\dot{x}_2 - \dot{x}_3) + k_1(x_2 - x_3) - k_2(x_2 - x_3) - F \tag{4}$$

Bond Graph was applied and a system with higher state space was obtained, but with similar dynamics, so it was decided to use this model for the application of the exact linearization technique.

The application of the exact linearization by feedback is a procedure that permits to transform the dynamics of a nonlinear system into a linear dynamics, through a previously chosen output. The result of the exact linearization of the system of equations (2), (3) and (4) for $k_i = \frac{P_i A_i}{x_i}$, $b_i = \frac{P_i A_i}{x_i}$, *i = 1, 2, 3*. In the description in the space of states, it is necessary to rewrite the system as:

$$\ddot{x}_1 = -\frac{b_1}{m}(\dot{x}_1 - \dot{x}_2) - \frac{k_1}{m}(x_1 - x_2) + \frac{1}{m}F$$
$$\ddot{x}_3 = -\left[\frac{b_1}{b_2}\frac{(b_1 + b_2)}{m}\right](\dot{x}_1 - \dot{x}_2) - \left[\frac{k_1}{b_2}\frac{(b_1 + b_2)}{m}\right](x_1 - x_2) + \left[\left(\frac{k_2 b_1 + k_1 b_2}{m b_2}\right)\right](x_2 - x_3) - \frac{1}{m}F \tag{6}$$

In (6), taking $(k_i = \frac{P_i A_i}{x_i})$, $(b_i = \frac{P_i A_i}{x_i})$, i = 1, 2, 3:

$$A = -\frac{b_1}{m};\ B = -\frac{k_1}{m};\ C = -\left[\frac{b_1}{b_2}\frac{(b_1+b_2)}{m}\right];\ \ D = -\left[\frac{k_1}{b_2}\frac{(b_1+b_2)}{m}\right];\ E = \left[\left(\frac{k_2 b_1 + k_1 b_2}{m b_2}\right)\right] \tag{7}$$

The system (6) is written as:

$$\ddot{x}_1 = A\dot{x}_1 - A\dot{x}_2 + Bx_1 - Bx_2 + \frac{1}{m}F;\ \ddot{x}_3 = C\dot{x}_1 - C\dot{x}_2 + Dx_1 - (D - E)x_2 - Ex_3 - \frac{1}{m}F \tag{8}$$

As u (t) = F (t) in state space, taking: $y_1 = x_1$, $y_3 = x_2$, $y_5 = x_3$, the system 8 is written as:

$$\begin{bmatrix}\dot{y}_1\\ \dot{y}_2\\ \dot{y}_3\\ \dot{y}_4\\ \dot{y}_5\\ \dot{y}_6\end{bmatrix} = \begin{bmatrix} y_2 \\ By_1 + Ay_2 - By_3 - Ay_4 \\ y_4 \\ 0 \\ y_6 \\ Dy_1 + Cy_2 - (D - E)y_3 - Cy_4 - Ey_5 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{m} \\ 0 \\ 0 \\ 0 \\ -\frac{1}{m}\end{bmatrix} \tag{9}$$

And, y = h (x) = y_3 - y_5. In (9), deriving the output, the degree of the system obtained is *r = 2*. For the construction of diffeomorphism $\phi(x) = (\mu, \psi)$, consider:

$$\phi = [y \quad \dot{y} \quad \psi_1\psi_2\psi_3\psi_4] = [y_3 - y_5, \quad y_4 - y_6, \quad \psi_2, \psi_3, \ \psi_4] = [\mu_1 \quad \mu_2 \quad \psi_1 \quad \psi_2\psi_3\psi_4] \tag{10}$$

where ψ_j, j = 1, 2, 3, 4 the solution for the PDE set: $\nabla\psi_j g = 0$ or

$$\frac{1}{m}\left[\frac{\partial\psi_j(x)}{\partial y_2} - \frac{\partial\psi_j(x)}{\partial y_6}\right] = 0 \tag{11}$$

A solution for the PDE given by Equation (9), is:

$$\psi_1 = y_1;\ \psi_2 = y_3;\ \psi_3 = y_4;\ \psi_4 = y_2 + y_6 \tag{12}$$

Hence, the function *φ(x)* can be written as:

$$\phi = [\mu_1, \mu_2, \psi_1, \psi_2, \psi_3, \psi_4] = [y_3 - y_5, y_4 - y_6, y_1, y_3, y_4, y_2 + y_6] \tag{13}$$

From Equation (13), it is evident that *φ(x)* is a global diffeomorphism. From Equation (10) and (11), is given:

$$y_1 = \psi_1;\quad y_5 = \mu_2 - \psi_3 + \psi_4;\quad y_3 = \psi_2; y_4 = \psi_3;\quad y_5 = -\mu_1 + \psi_2;\quad y_6 = -\mu_2 + \psi_3 \tag{14}$$

The normal form of the dynamic (9) is given asr:

$$\begin{bmatrix} \dot{\mu}_1 \\ \dot{\mu}_2 \\ \dot{\psi}_1 \\ \dot{\psi}_2 \\ \dot{\psi}_3 \\ \dot{\psi}_4 \end{bmatrix} = \begin{bmatrix} \mu_2 \\ -E\mu_1 - C\mu_2 - D\psi_1 + D\psi_2 + 2C\psi_3 - C\psi_4 + \frac{1}{m}u(t) \\ \mu_2 - \psi_3 + \psi_4 \\ \psi_3 \\ 0 \\ -E\mu_1 + (A+C)\mu_2 + (B+D)\psi_1 - (B+D)\psi_2 - 2(A+C)\psi_3 + (A+C)\psi_4 \end{bmatrix} \tag{15}$$

In (15), the internal dynamic is nonlinear:

$$\begin{bmatrix} \dot{\psi}_1 \\ \dot{\psi}_2 \\ \dot{\psi}_3 \\ \dot{\psi}_4 \end{bmatrix} = \begin{bmatrix} \mu_2 - \psi_3 + \psi_4 \\ \psi_3 \\ 0 \\ E\mu_1 + (A+C)\mu_2 + (B+D)\psi_1 - (B+D)\psi_2 - 2(A+C)\psi_3 + (A+C)\psi_4 \end{bmatrix} \tag{16}$$

Where:

$$A + C = -\left(\frac{P_1A_1}{m}\right)\frac{1}{(\mu_2-\psi_3+\psi_4)} \cdot \left[2 + \left(\frac{P_1A_1}{P_2A_2}\right) \cdot \frac{\psi_3}{(\mu_2-\psi_3+\psi_4)}\right] \text{ and}$$
$$B + D = -\left(\frac{P_1A_1}{m}\right)\frac{1}{\psi_1}\left[2 + \left(\frac{P_1A_1}{P_2A_2}\right) \cdot \frac{\psi_3}{(\mu_2 - \psi_3 + \psi_4)}\right]$$

The dynamic zero is obtained from the dynamic (16) when the output y = 0. Hence, μ1 = μ2 = 0. This dynamic has equations:

$$\begin{bmatrix} \dot{\psi}_1 \\ \dot{\psi}_2 \\ \dot{\psi}_3 \\ \dot{\psi}_4 \end{bmatrix} = \begin{bmatrix} -\psi_3 + \psi_4 \\ \psi_3 \\ 0 \\ (B+D)\psi_1 - (B+D)\psi_2 - 2(A+C)\psi_3 + (A+C)\psi_4 \end{bmatrix} \tag{17}$$

Where, in such conditions:

$$A + C = -\left(\frac{P_1A_1}{m}\right)\frac{1}{(-\psi_3 + \psi_4)}\left[2 + \left(\frac{P_1A_1}{P_2A_2}\right) \cdot \frac{\psi_3}{(-\psi_3 + \psi_4)}\right];$$
$$B + D = -\left(\frac{P_1A_1}{m}\right)\frac{1}{\psi_1}\left[2 + \left(\frac{P_1A_1}{P_2A_2}\right) \cdot \frac{\psi_3}{(-\psi_3 + \psi_4)}\right]$$

For the calculation of the critical points of (17) it is shown that que $\psi_1 = \psi_3 = \psi_4 = 0$ and ψ_2 is free. Therefore, (0, 0, 0, 0) is a critical point of this dynamic. The matrix A of the linear counterpart of the dynamic (17) is:

$$A = \begin{bmatrix} 0 & 0 & -1 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

Moreover, its characteristic equation is given by: $\lambda^4 = 0$.

RESULTS

From the simplifying proposal of the mass-spring-damper model for the human esophagus, it was possible to continue the study of the dynamics of the organ behavior as a function of the speed and displacement of the food bolus. Thus, when applying the open-loop system of the healthy esophagus on Matlab's Simscape program, the system response presents the position of the mass as a function of time. Thus, for 1N of input force, the mass displacement is 8 cm in 25 seconds. However, for the same input, the chagasic megaesophagus system has a 6.25% shorter displacement for the same time scale.

The result is consistent with the literature, since when the esophagus is affected by Chagas' disease the degree of denervation of the intramural plexus is approximately 90%[6,17], which results in muscle hypertrophy and motor incoordination, implying the reduction of contraction pressure of the esophageal body to values below 20mmHg.

Through the simulations carried out in the Simscape™, it was possible to analyze and compare the dynamics for both models. In the healthy esophagus, the velocity curve, shown in Figure 2, was obtained when the system was induced by a pulse of 5N and 7 seconds, equivalent to the time required for the peristaltic wave to reach the end of the esophagus. Thus, it is possible to evaluate, in terms of the speed of the wave (which was considered in the calculations of k and b) and its duration, what the speed of the food bolus and its displacement will be. As can be seen in the velocity curve, at first, the mass is at rest and at 2 seconds, due to the input signal abrupt change, the mass velocity peaks in the positive direction and gradually returns to zero.

The displacement changes gradually and reaches its maximum value at the end of the force acting at 9 seconds, due to inertia and damping. At this point, the input signal returns to zero, the velocity has an inverse peak, and the mass gradually returns to its initial position. The mass moves approximately 25 cm, which roughly corresponds to the extension between the upper and lower esophageal sphincters.

The graph of Figure 2 shows the output of the healthy esophagus system from the model on Figure 1 and the response of the chagasic megaesophagus when induced by a unit step input.

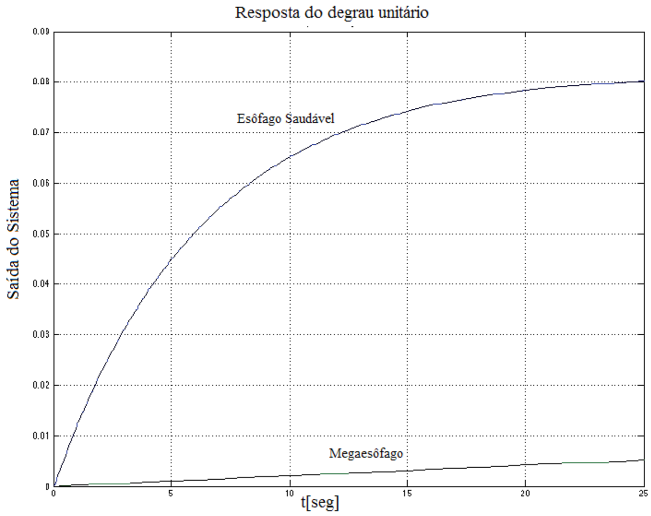
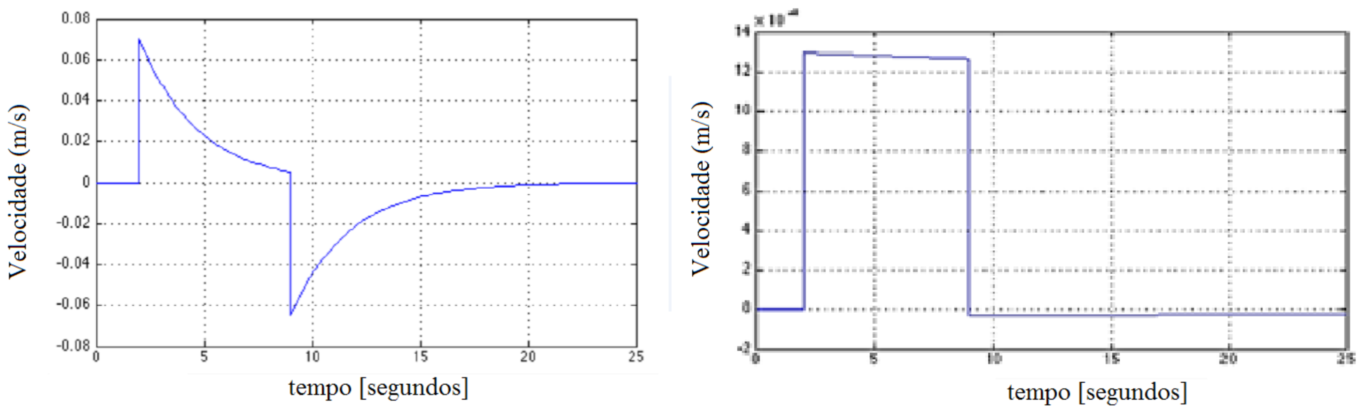


Figure 2: Responses of the healthy esophagus and the chagasic megaesophagus when induced by a step input – 2015.

The same analysis is applied to measure the velocity in order to understand the dynamics of the chagasic megaesophagus compared to the healthy esophagus. In the graphs of Figure 3, a virtually zero velocity (approximately 1.2 mm/s) occurs during the 7 seconds that the force is applied by displacement.



(a) (b)

Figure 3: (a) Velocity curve for the healthy esophagus system. Velocity curve for the chagasic megaesophagus system – 2015.

DISCUSSION

Considering the response curve of the two systems under study, that is, the healthy esophagus and the chagasic megaesophagus, it was possible to design, from their open loop responses, a gain controller capable of approaching the curve of the diseased esophagus to the curve of the healthy esophagus. The controller design initially considers the healthy system transfer function. In other words, if the organ were to have no functionality, the controller would completely perform the competent biological functions, acting as a regulator of the physiological limitations. However, considering as an example the proposed model for a case of Type II Chagasic Megaesophagus with dilatation of 6 cm of esophageal transverse diameter, the organ still presents a response equivalent to 6.25% of performance in the food displacement. Thus, replacing the values yields the proposed transfer function for the Organic Controller, which should have a performance rate of 93.75% in relation to the T.F. of the healthy esophagus, since the difference is compensated by the output obtained by the diseased organ. Therefore, the transfer function of the Organic Controller will be given by equation (22).

$$FT = (0.9375)x\frac{1}{0{,}005s^2+76.739s+12.246} \qquad (22)$$

The output obtained by the organic controller characterized by the Transfer Function described in Equation 22 plus the natural output of the chagasic megaesophagus will provide a final output closer to the ideal and with a dynamic performance equivalent to the healthy organ, according to Figure 4.

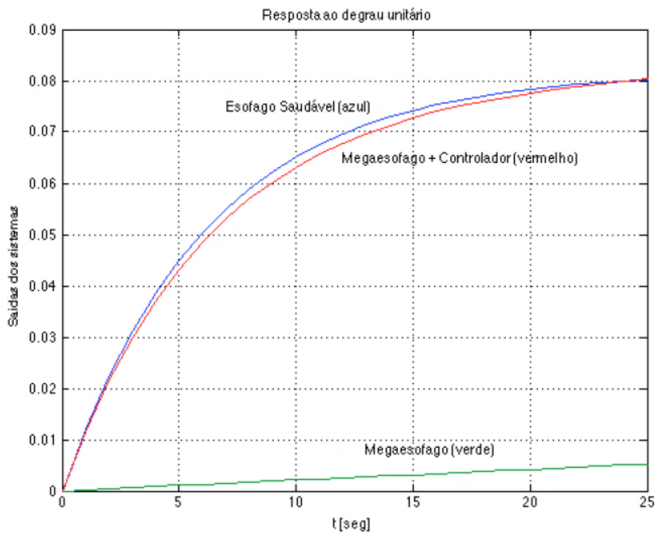
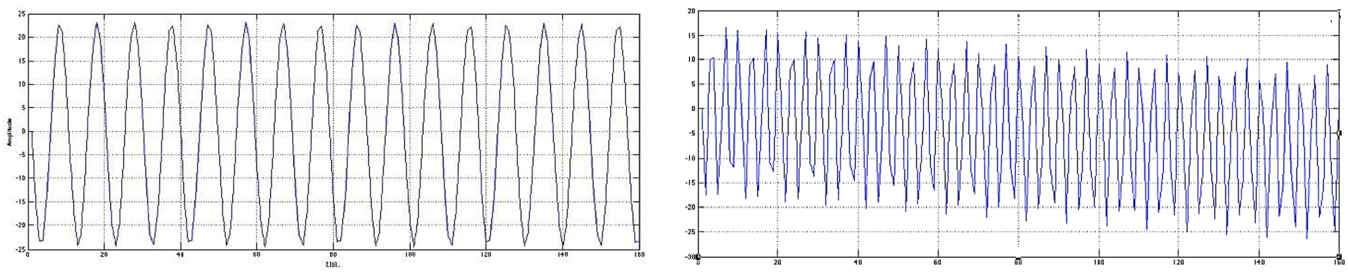


Figure 4: System response, lower curve, due to the performance of the organic controller in the chagasic megaesophagus when induced by a step input – 2015.

For the analysis of the dynamic system proposed by the model of Figure 1 and for the identification of its performance, the system was induced by means of a standardized signal. Through the simulation, the response of the system when induced by the input step has allowed to define its performance characteristics. The dynamic behavior was altered compared to the normal esophagus, according to Figure 5, where y is the dimensionless amplitude and x the time in seconds.



(a) (b)

Figure 5: (a) Healthy esophageal system response to a step input; simulated in MatLaB Student – 2015.

Chagasic megaesophagus also presented altered dynamics when compared to the healthy esophagus. According to the results, the response of the system to the diseased esophagus is highly oscillatory, implying a slower response. Moreover, progressive decay of the amplitude when the system is induced by a step input reflects the inefficiency of maintaining a dynamic capable of displacing the ingested food.

CONCLUSION

A human esophagus model was developed with the parameters of a chagasic megaesophagus. By means of this model, an organic controller introduced to the chagasic megaesophagus system was proposed to revert the chiarosclerosis of the organ when it is affected by Chagas' disease.

The mathematical proposal for the controller was applied and satisfactory results were obtained in the approximation of the performance curve of a grade II megaesophagus in relation to the healthy organ curve, after receiving the aid of the organic controller. By analyzing the results, it was seen that the output of the controller added to the output of the system acts on the propagation of artificial peristaltic waves in the diseased organ, increasing its function at a rate of 93.75% in relation to that of a healthy esophagus.

Thus, by means of organ monitoring and sensing device, the correction of the output signal and, consequently, of the dynamic activities of the organ will be performed, allowing an improvement in the clinical picture of patients with chagasic megaesophagus.

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