# Bond Graph modeling of the human esophagus and analysis considering the interference in the fullness of an individual by reducing mechanical esophageal flow

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**Abstract**    **Introduction:** *This paper shows a proposal for the mathematical modeling of the human esophagus using Bond Graph formalism and the interference in the satiation of an individual by way of an Esophageal Flow Controller (EFC). Therefore, it was evaluated that there is a significant change in fall time that affects the process of human satiety when the diameter of the esophagus is reduced.* **Methods:** *As a first study, the analysis did not consider all hypothetical influences; only the most important variables were considered.* **Results:** *As a result, the order of the final equation was* $x \in \Re^{10}$. *Furthermore, the designed model can be classified as linear, established and time invariant.* **Conclusion:** *The simulation results allow us to conclude that using the EFC in order to reduce the esophageal diameter in the upper esophageal sphincter area of 3 cm by 1 cm implies that the system response will be slower; and consequently this reduction will interfere with satiety.*

**Keywords**    *Math modeling, Bond graph, Esophagus, Control.*

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# Introduction

Decreased food intake is due to the obstructive processes of the esophagus, as proposed by Rosa (2009). Furthermore, according to Rosa (2009) it is possible to insert a device that can reduce the esophagus's diameter. This device, called an EFC, causes resistance to passage of the bolus when inserted into the esophagus and the result is slower food intake. The need for prolonged mastication occurs due to the reduction in esophageal lumen. This effect on chewing influences the triggering mechanisms of satiety and implies nutritional re-education and consequent weight loss. Thus, a model of the human esophagus is important to understand the interference in satiety when the EFC is used.

In the literature, analyses of bolus motion have already been proposed. However, the modeling that relates pathologies and the passage of the bolus through the esophagus still persist almost entirely based on this binary; they do not evaluate, for example, the interference in satiety.

## *The Human Esophagus*

The esophagus is a fibrous-mucosal-muscular tube which extends between the pharynx and stomach. It has a mean length of 25 cm (40 cm from the incisors), with 3 cm of lateral diameter and 2 cm of anteroposterior diameter in adults. It consists of three portions: cervical, thoracic and abdominal. The cervical esophagus is about 5 cm long; it starts below the upper esophageal sphincter (UES) and goes to the 1st thoracic vertebra. The thoracic esophagus measures 16-18 cm in length. When it enters the chest, the path of the esophagus is no longer straight, deviating slightly to the left and crossing the left bronchus. It is situated between the vertebrae, the trachea and the lungs (Rosa, 2009). In living individuals, it is very mobile. The lungs, heart and major arteries pulse rhythmically, and the esophagus distends to the extent that the bolus passes through it (Tortora, 2000). There is also within this framework a fixation of the esophagus to the left main bronchus through the bronchio-esophageal muscle. In addition, to the right it is crossed by the arch of the azygos vein (a vein of the thorax). On the left, the esophagus is connected to the left recurrent laryngeal nerve, the origin of the left subclavian and carotid arteries; near the thoracic duct and the arch of the aorta (which promotes broncheo-aortic narrowing, for which reason the esophagus measures only 15 to 17 mm in diameter at that level) there is a constriction. In the intra-bronchial portion, the esophagus deviates slightly to the middle line several centimeters above the diaphragm. When the esophagus passes behind the heart, it deviates to the left again. Subsequently, the esophagus passes near the backbone (level between the 4th and 11th thoracic vertebra), the descending aorta, the azygos vein and thoracic duct segments beyond the pleural reflection (Paula, 2010). Figure 1 shows the system under study.

## *Main features*

The basic function of the esophagus is to transport swallowed material from the mouth to the stomach and occasionally in the opposite direction; it has a sphincter at each end with the main purpose of keeping it empty, avoiding the entry of air at the top and gastric contents at the bottom. When evaluating the physiological control mechanisms that involve this organ, the muscle of the esophagus, which is responsible for motility, is formed by a circular (internal) and a longitudinal (external) layer. It begins with the voluntary movement of the tongue, which causes an involuntary peristaltic wave, which travels rapidly, reaching the upper esophageal sphincter (pharyngoesophageal sphincter) and producing a rapid and coordinated relaxation followed by a contraction after swallowing. Muscle fibers found in the distal 55 to 60% of the esophagus are the smooth type, while in the proximal 10% the fibers are ribbed; in the intermediate portion, there are mixed smooth and striated fibers (Dantas *et al*., 2010; Trawitzki *et al*.,



**Figure 1.** Handmade drawing of the system under study.

2010). In Paula (2010) it is reported that the speed of the peristaltic wave corresponds exactly to the contraction manometrically verified. These peristaltic waves have durations between 3.0 and 4.5 seconds and reach their maximum amplitude at 60 to 140 mmHg in the lower (distal) esophagus. The contractions are repeated in waves that push the food into the stomach. The passage of solid or semisolid food from the mouth to the stomach takes 4 to 8 seconds; very soft and liquid foods take about 1 second, as shown in the cited reference in the description of the primary peristaltic wave: i) speed: 4.0 to 6.0 cm/s ii) time: 3.0 to 4.5 s and iii) amplitude: 60 to 140 mmHg. Importantly noted is the travel time of food through the esophagus: consistence and time (s): i) solids or semi-solids equal 4.0 to 8.0 and ii) fluids equal 1.0.

Therefore, the aim of this study was to propose a mathematical modeling of the human esophagus considering the interference in the individual satiety due to the EFC. Along with the modeling techniques, Bond Graph theory will be used for the representation of the system under study. Bond Graph theory is a unified representation of dynamic systems, in which elements interact with one another via ports allocated within the system where the exchange of energy occurs (Gawthrop, 1996; Karnopp *et al*., 2000; Paynter, 1992; Rosenberg, 1993).

As the application of this device for esophageal treatments already occurs in clinical practice, a mathematical model is important to evaluate via computational simulation the dynamic response of the system. Thus, it will be investigated if using the EFC in order to reduce the diameter of the esophagus in the upper esophageal sphincter area implies that the system response will be slower and consequently will interfere with the individual's satiation. The results will allow for a better understanding of the passage of food though the esophagus, the establishment of the relative influence of some parameters and the properties of the appetite regulation process.

## Methods

The research methodology adopted to obtain the mathematical model can be defined in three steps:

i)   Specify the analog system based on the real physiological model;
ii)  Determine the energy domains;
iii) Define the simplified hypotheses and the input and output variables of the system.

The description of each component of the model is presented, divided into the following topics:

### Specified system of study

The human esophagus was modeled based on the description of the esophageal structure, its surrounding elements and its function. The modeling based on items that directly and indirectly influence the process allows the development of a complex model that enables dynamic responses to be valid in a wide range of operations (Marlin, 2010).

As discussed by the authors, with regards to the esophagus all data indicate high uncertainties due to the following factors: spatial distribution of the organ, type and size of the individual and lack of data in the literature.

The esophagus was modeled by combining methodologies to approximate the real system with an analogous system- in this case, the mechanical-hydraulic, using the *Bond Graph* tool to obtain the state variables. Figure 2 shows the conversion of the physiological system into its mechanical-hydraulic analogue.

An advantage of the *Bond Graph* modeling technique is the division of the system into subsystems, and the energy or power variable occurs in pairs: pressure-flow; force-velocity; torque-angular velocity and voltage-current. These are pairs that make the connections between the subsystems - called ports. Table 1 shows the analogs of the real variables in the *Bond Graph* technique. In these tables, the variables are classified as energy dissipators, storers, transformers, generators and sources.

### Energy domains

The energy domains are essential to understand the physiological system using the *Bond Graph* theory. Thus, it was important to design a simplified representation of the rotational mechanical-hydraulic and translational processes involved in the passage of the food trough the esophagus. For a better understanding, see below a description of each modeled region of the system (A, B, C, D, E, F).

### Region A

The region of the mouth receives food from a source of effort. Broadly speaking, there are two generalized variables – effort and flow, whose product represents the power that runs through the system. In the case of the system modeled, the power refers to the passage of the bolus. The food reception process was represented by the translational mechanical analogue.

For the masticatory process, we made an analogue to the hydraulic system. The system was considered analogous to a hydraulic cylinder, where the process has pressure, flow, fluidic resistance and fluidic capacity.

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**Table 1.** Analogues of real variables by *Bond Granph* technique.

| Variable | Description of real system | description of analogous system | *Bond Graph* |
|---|---|---|---|
| | **Region A: region of the human mouth** | | |
| Fo | Initial input force of food into the mouth - input system. | Force applied under the area of the hydraulic cylindrical piston. | Mechanical - translational flow. |
| Vo | Initial input velocity of food into the mouth. | Velocity applied under the area of the hydraulic cylindrical piston. | Mechanical -translational effort. |
| A0 | Area of the region of the mouth where the food is processed generating the bolus. | Area of the cylindrical piston. | GY – is the transformation relation – r = 1/A0. |
| Rfo | Loss of load or difficulty imposed during mastication, tongue, teeth and saliva mixture. | Friction inside the mouth - dimensionless, is a factor which ranges from 0 to 1 and simulates friction. For younger people, the friction is higher. As for the elderly friction is lower. | Resistor – dissipates energy. |
| Po | Saliva and food for simulating the bolus. | Hydraulic pressure. | Effort - hydraulic. |
| Cfo | Volume of the bolus taking into account the specific mass of the fluid - similar to the reservoir. | Hydraulic capacitance. | C – energy stored, P = V/C. |
| Qo | Volume flow rate of the bolus when leaving the mouth region. | Hydraulic flow. | Flow - hydraulic. |
| | **Region B: epiglottis** | | |
| P1x | Input pressure of the bolus in this region. | Input pressure. | Hydraulic effort, in a 1-junction. |
| R | Epiglottis and the resistances to the passage of food. | Resistance to the volume flow rate (laminar flow and without gas). | Resistor – dissipates energy. |
| P2x | Bolus pressure in this region. | Flow pressure. | Hydraulic effort, in a 1-junction. |
| Rf1 | Cricoid cartilage. | Restriction imposed by cartilage - changes the fluid flow velocity. | Resistor – dissipates energy and changes the fluid flow velocity. |
| Rf2 | Cricoid cartilage. | Restriction imposed by cartilage - changes the fluid flow velocity. | Resistor – dissipates energy and changes the fluid flow velocity. |
| P3x | Output pressure of the bolus in this region. | Output pressure. | Hydraulic effort, in a 1-junction. |
| | **Region C: UES and singularity** | | |
| Q1x | Volumetric flow rate of the bolus in the esophagus. | Flow through a lossless pipe, incompressible fluid. | Hydraulic flow - coming from the region B. Junction 1, common flow. In this region, the flow keeps the same. |
| Rf3 | The resistance in this region is due to tissue and cartilage. | Fluidic resistance - RF, TR as a function of absolute viscosity and internal diameter. | RF and TR are defined as turbulent flow in rough pipe and are a function of friction factor, as defined by (Garcia, 2009, p. 278). |
| P4x | Output pressure of the bolus with an abrupt change; function of the friction factor (fa) of the Moody L.F. diagram. | Output pressure that will act on piston system generating mechanical movement. | Hydraulic effort - GY input - to change the domain power. |
| | **Region D: cervical esophagus** | | |
| A1 | Area according to the diameter (d1) of the esophagus in this region; it is considered the maximum opening passage. | Area of the cylindrical piston. | GY – is the transformation relation – r1 = 1/A1. |

**Table 1.** Continued...

| Variable | Description of real system | description of analogous system | *Bond Graph* |
|---|---|---|---|
| | | **Região D1 – bronchia** | |
| KH | Influence of the bronchi. | Rigidity of the shaft. | C – energy stored, P = V/C; it changes the effort; 0 - junction, mechanical-translational. |
| BH | Influence of the bronchi. | Shaft cushion. | R: BH – mechanical-translational. |
| | | **Region D2 – cervical esophagus** | |
| mL | Mass of bolus - uniform. | Mechanical linear mass. | Inertial port – I – varies the amount of the motion (p = m·V). |
| Fb | Friction of the bolus with the smooth and striated fibers wall of the esophagus. The presence of megaesophagus leads to difficulty in swallowing, it takes the name of dysphagia. It is not uncommon patients with achalasia present ulcers due to constant friction of the bolus. | Load friction. | Resistor – dissipates energy; changes the effort; 0 - junction. |
| K2 | Resistance via a spring (variation of speed and displacement). | Rigidity of the spring. | Capacitive. |
| B2 | It is the speed variation of the bolus in the process of descent. | Viscous friction. | Resistance. |
| H | Represents the rotational movement of the bolus into the esophagus. | Pitch of the screw. | TF = h. |
| JL | Represents the resistance of the bolus to the acceleration generated by peristalsis. | Rotational inertia. | Angular inertance - I. |
| Bm | Resistance to torque variation of the bolus proportional to angular velocity. | Friction of the JL with the esophageal wall. | Resistor – R. |
| D | Displacement of the bolus in the region of the cervical esophagus. | Transformation for rotational to translation. | TF:d. |
| m2 | Mass of the bolus. | Translational mass. | Inertia I. |
| B3 | Bolus friction due to the bolus passage through the esophagus wall. | Linear friction. | Resistor R. |
| | | **Region E: thoracic esophagus** | |
| K3 | Resistance force of the bolus due to the peristaltic force. | Linear spring. | Capacitance. |
| m3 | Mass of the bolus. | Translational mass. | Inertia. |
| B4 | Bolus friction due to the bolus passage through the esophagus wall. | Linear friction. | Resistor R. |
| | | **Region E: abdominal portion of the esophagus** | |
| K4 | Resistance force of the bolus due to the peristaltic force. | Linear spring. | Capacitance. |
| m4 | Mass of the bolus. | Translational mass. | Inertia. |
| B5 | Bolus friction due to the bolus passage through the esophagus wall. | Linear friction. | Resistor R. |
| | | **Region F: LES** | |
| A2 | LES area (sphincter diameter d2). | Area of the cylindrical piston. | GY – is the transformation relation – r = 1/A2. |
| Rf5 | Bolus friction due to the bolus passage through the LES. | Hydraulic resistance. | Resistance. |
| Q2 | Mass of the bolus. | Output flow of the bolus at LES exit. | Output signal. |

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We adopted a few assumptions, such as: compressible fluid, laminar flow with losses and specific mass ρ constant. In this case, the variable effort (which in the *Bond Graph* is the pressure) will remain the same in this region, given the previous assumptions.

### Region B

Upon exiting the mouth, the flow $Q_0$, which corresponds to the bolus with saliva, enters region B, which corresponds to the final region of the mouth and

pharynx (epiglottis). Thereafter, the flow through the orifice is similar to a laminar flow, since $R_e^{-1} < 1100$ (Garcia, 2009). In this region, we assumed a fluidic resistance $R_{Fi}$ (i = 1, ... 3) which refers to the loss of load along the circuit.

### Region C

The output of this part of the circuit generates a flow $Q_1$ and a pressure $P_{3x}$ which refer to the passage of the bolus through the region C. This region of the system is similar to the flow through a capillary tube, which will be considered laminar (linear), but rough (rough tube) due to the friction. In this region, due to the azygos veins, aortic arch and the influence of the vertebra, we considered the loss of pressure and flow variation as change from the hydraulic energy domain to mechanical-translational. In this region, the influence of diameter, d, must be analyzed in the mathematical model.

### Region D

In region D, the ingested material is propelled along the lumen of the esophagus by two types of forces: the gravitational force and the peristaltic-type force of contraction executed by the muscles of the organ itself, which is able to move the content in the craniocaudal direction, even against gravity or with the body in a supine position. In the erect position, the esophageal transit occurs within 10 seconds. The propulsive movement which, after ingestion, runs the length of the esophagus in craniocaudal direction is called primary peristalsis. The peristalsis triggered by the presence of any liquid or solid material in the lumen of the organ, regardless of swallowing, is called secondary peristalsis (Guyton and Hall, 2006). This region includes the trachea, thoracic duct, laryngeal nerve, left and right lungs and blood vessels. In the transition between the pharynx and esophagus where the cricopharyngeal muscle is connected is where the upper esophageal sphincter (UES) is located. The UES is formed by innervated striated muscles, primarily innervated by the vagus nerve, which act in the modeled process as physical variables of the system.

### Regions E and F

Steps E and F of the circuit refer to the esophagus in the abdominal portion between the esophageal body and the stomach, which the lower esophageal sphincter (LES) interposes. The intra-esophageal pressure is lower than the intra-gastric; the LES is characterized by being a zone of 2 to 4 cm of extension with higher
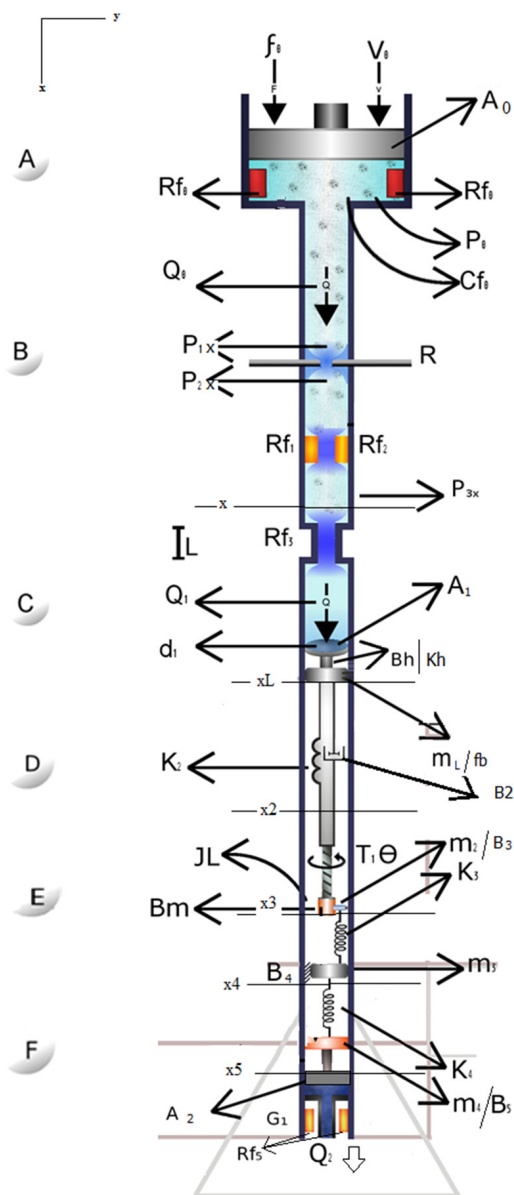


**Figure 2.** Mechanical and hydraulic representation analogous to the esophagus system, and its variables and constants.

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[1] Reynolds number $= R_e = \dfrac{\rho D \upsilon}{\mu}$, (Garcia, 2009).

pressure than the stomach and is therefore an effective barrier against the gastro-esophageal reflux (Fernandes, 2006). In this region, we sought to represent the entire process of muscle and pressure waves and pleural interference by a torsional spring and a linear spring. The LES can also indicate spontaneous contractions and incomplete relaxation; the representation for such phenomena was made by changing the domain and resistance $R_{F5}$.

### Simplifying assumptions and parameters adopted

Some considerations were assumed in the modeling of the system:

- The bolus is uniform in its geometric structure;
- The volume of saliva is fixed;
- The system parameters are concentrated;
- It is assumed that there is noise in the system;
- The influence of a few surrounding organs and systems was ignored;
- The pharynx implies inertial effects.

Table 2 shows the values adopted for the system constants. Further details on the equivalence of each constant and the calculation developed can be seen in Table 1. To obtain these variables, we used the values already available in the literature and equations that allowed the acquisition of the magnitude required. In addition, for the study we used a geographically homogeneous population in order to avoid errors in comparison with other populations affected by various factors, since according to Salomão *et al*. (2004) the esophageal manometry still has no universal standardization for obtaining data.

## Results

### Bond Graph mathematical model

The *Bond Graph* model proposed for the esophageal system was structured using the simulation software 20-sim. Just one derivative causality has been identified. The causality determines how the generalized element can store energy and interact producing the dynamic interactions of the system. Figure 3 demonstrates the modeling obtained in *Bond Graph* language.

To obtain the equations in state space, the system was simplified through the software 20-sim. Figure 4 shows the simplified diagram.

In the simplified process, the software analyzed the power and energy receptors and eliminated redundancies. After the *Bond Graph* simplified model, the equations were obtained to construct the matrix

**Table 2.** Values adopted for the variables that comprise the esophagus model. Data relating to healthy subjects from a locoregional population.

| System Constants | | | |
|---|---|---|---|
| $R$ | $221,435.87 \left[\dfrac{Pa \cdot s}{m^4}\right]$ | $B_4$ | $0.3917 \left[\dfrac{N}{m}\right]$ |
| $R_{fo}$ | $0:0.01:1$ | $B_5$ | $0.446 \left[\dfrac{N}{m}\right]$ |
| $R_{f1}$ | $1,112,413.31 \left[\dfrac{Pa \cdot s}{m^4}\right]$ | $B_H$ | $7.093 \left[\dfrac{N \cdot 10^{-6}}{m}\right]$ |
| $R_{f2}$ | $1,112,413.31 \left[\dfrac{Pa \cdot s}{m^4}\right]$ | $F_b$ | $1.531 \left[\dfrac{N}{m}\right]$ |
| $R_{f3}$ | $1,070,743.10 \left[\dfrac{Pa \cdot s}{m^4}\right]$ | $m_L$ | $5 \cdot 10^{-3}$ [kg] |
| $R_{f5}$ | $111,724.46 \left[\dfrac{Pa \cdot s}{m^4}\right]$ | $m_2$ | $5 \cdot 10^{-3}$ [kg] |
| $C_{fo}$ | $4.99 \times 10^{-4} \left[\dfrac{m^5}{N}\right]$ | $m_3$ | $5 \cdot 10^{-3}$ [kg] |
| $K_2$ | $3.12 \left[\dfrac{N \cdot 10^{-6}}{m}\right]$ | $m_4$ | $5 \cdot 10^{-3}$ [kg] |
| $K_3$ | $0.1560 \left[\dfrac{N}{m}\right]$ | $J_L$ | $5 \cdot 10^{-3}$ [kg] |
| $K_4$ | $0.254 \left[\dfrac{N}{m}\right]$ | $A_0$ | $7.065 \cdot 10^{-4}$ [m²] |
| $K_H$ | $10.318 \left[\dfrac{N \cdot 10^{-6}}{m}\right]$ | $A_1$ | $8.24 \cdot 10^{-7}$ [m²] |
| $B_m$ | $1.079 \times 10^{-3} \left[\dfrac{N \cdot 10^{-6}}{rad}\right]$ | $A_2$ | $1.49 \cdot 10^{-6}$ [m²] |
| $B_2$ | $4.34 \left[\dfrac{N \cdot 10^{-6}}{m}\right]$ | $h$ | $2.5 \cdot 10^{-3}$ [m] |
| $B_3$ | $0.2167 \left[\dfrac{N \cdot s}{m}\right]$ | $n$ | $1$ |

of state space. Equation 1 shows the matrix of state space for the system modeled. Table 3 presents the classification obtained from matrix analysis of state space of the modeled system.

### General dynamics of the esophageal system

The state space matrix was simulated in Matlab using the values indicated in Table 1. The system response, when stimulated with step input, indicates a stable behavior with system characteristics of the first order, as shown in Equation 1. For this simulated output, three different values for $R_{f0}$ were adopted.

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$$
\begin{bmatrix}
\dot{x}_1 \\ \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \\ \dot{x}_5 \\ \dot{x}_6 \\ \dot{x}_7 \\ \dot{x}_8 \\ \dot{x}_9 \\ \dot{x}_{10}
\end{bmatrix}
=
\begin{bmatrix}
-\dfrac{1}{Cfo}\left(\dfrac{1}{Rfo}+\dfrac{1}{R}+\dfrac{1}{Rf1}+\dfrac{1}{Rf2}+\dfrac{1}{Rf3}\right) & 0 & 0 & \dfrac{1}{A_1 Cfo} & 0 & 0 & 0 & 0 & 0 & 0 \\[2mm]
0 & -\dfrac{1}{B_H K_H} & 0 & \dfrac{1}{B_H K_H} & 0 & 0 & 0 & 0 & 0 & 0 \\[2mm]
0 & 0 & \dfrac{Fb}{mL} & -\dfrac{1}{mL} & 0 & 0 & 0 & 0 & 0 & 0 \\[2mm]
-\dfrac{1}{A_1 K_2} & -\dfrac{1}{B_H K_2} & \dfrac{1}{K_2} & \dfrac{A_1}{hB_m K_2} & -\dfrac{1}{hK_2} & \dfrac{B_3 K_4}{nhK_2} & \dfrac{K_3}{nhK_2} & \dfrac{K_4}{nhK_2} & 0 & 0 \\[2mm]
-\dfrac{1}{B_H K_2} & -\dfrac{1}{B_2 K_2} & 0 & 0 & 0 & 0 & \dfrac{A_1 K_3}{hn^2 K_2} & -\dfrac{A_1 K_4}{hn^2 K_2} & 0 & 0 \\[2mm]
0 & 0 & 0 & \dfrac{1}{hJ_L} & 0 & 0 & 0 & 0 & 0 & 0 \\[2mm]
0 & 0 & 0 & \dfrac{1}{hnm_2} & 0 & -\dfrac{B_3}{m_2} & 0 & 0 & 0 & 0 \\[2mm]
0 & 0 & 0 & -\dfrac{Rf_5 A_2^2}{hK_3} & 0 & 0 & 0 & 0 & 0 & 0 \\[2mm]
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \dfrac{1}{K_4} & \dfrac{1}{K_4} \\[2mm]
0 & 0 & 0 & \dfrac{1}{hm_3} & 0 & 0 & 0 & 0 & -\dfrac{B_4}{m_3} & 0 \\[2mm]
0 & 0 & 0 & \dfrac{1}{hm_4} & 0 & 0 & 0 & 0 & 0 & -\dfrac{B_5}{m_4}
\end{bmatrix}
\cdot
\begin{bmatrix}
x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \\ x_8 \\ x_9 \\ x_{10}
\end{bmatrix}
+
\begin{bmatrix}
A0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0
\end{bmatrix}
\cdot \big[ fo(t) \big]
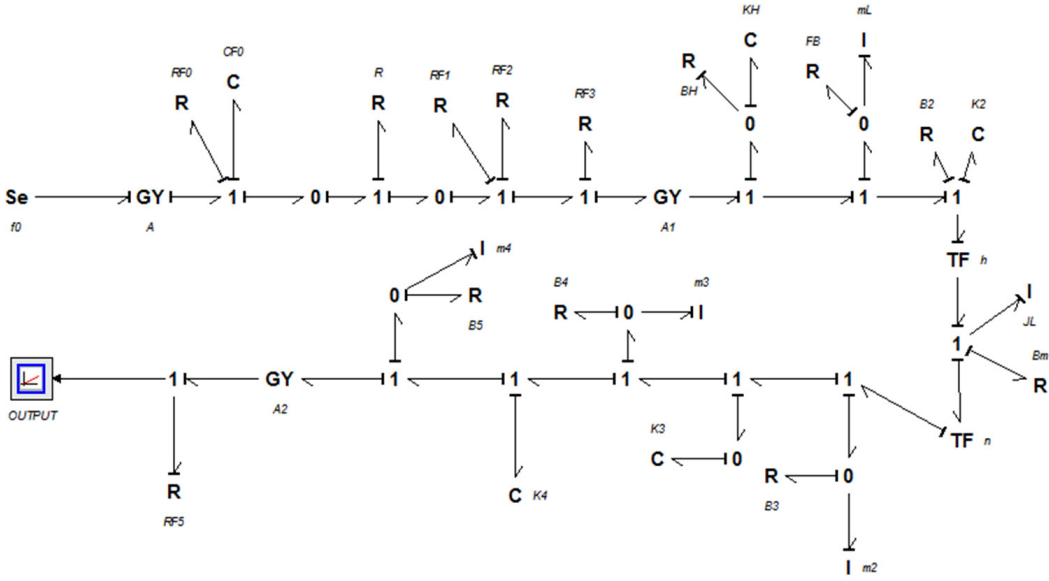\qquad (1)
$$

**Figure 3.** *Bond Graph* Model of the human esophagus.



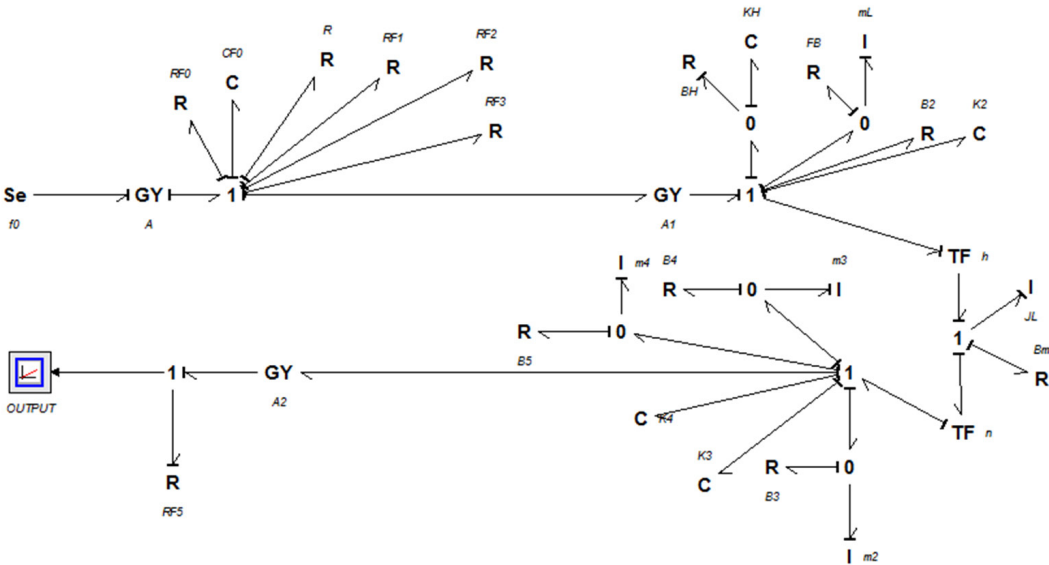**Figure 4.** Simplified *Bond Graph* model of human esophagus.

**Table 3.** Classification of the modeled system in the form of state space.

| System | | Classification |
|---|---|---|
| Input vector | *fo* (t) | Order: $x \in \Re^{10}$ |
| Matrix A | Dimension 10 × 10 | Explicit System |
| Matrix B | Dimension 10 × 1 | No algebric loop |
| Matrix C | Dimension 1 × 10 | SISO |
| Matrix D | Null | Linear |
| | | Time-invariant |
| | | Continuos |
| | | Parameters concentrates |
| | | Deterministic |

When plotting the response of each state, it is apparent which states influence the behavior of the system. In Figure 5a, b it can be seen that states x1 and x4, with orders 5 and 9 respectively, are the states of greater influence.

### *Internal dynamics of the esophageal system*

The impulse response shows asymptotic internal stability of the system, as can be seen in Figure 6a. In Figure 6 b, we can see that the eigenvalues, different

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or with repetition, are in the left semi-plan providing stability to the system.

### *Performance of Esophageal Flow Controller - EFC*

In order to discuss the relationship between setting the esophagus diameter and resistance to the passage of the bolus in the esophagus, two simulations were conducted. Thus, it was evaluated that if there is some significant change in the fall period, it affects the process of human satiety.

First, we considered the extension of the esophagus as a tube of 3 cm diameter. Thus, we attributed $A_0$, $A_1$ and $A_2$ equal to 3 cm and excited the system with a pulse stimulus. When the performance of the EFC was evaluated, the area of the upper sphincter region ($A_1$) was reduced to an area with a diameter of 1 cm.

Thus, the results obtained for comparison can be seen in Figure 7a, b.

## Discussion

As a first study, the analysis did not consider all hypothetical influences. As a result, the order of the final equation was $x \in \Re^{10}$. The temporal response of the modeled system to the unit step input indicates that the process has a fast time constant which is characteristic of systems derivatives.

Thus, there is an attenuation of the input signal, where it is inferred that the simulated model matches the dynamic intake; in other words, when the force and input speed of a liquid is quick but its resistance is low, the level of energy to expended transport food decreases and the pressure of the esophagus decreases.
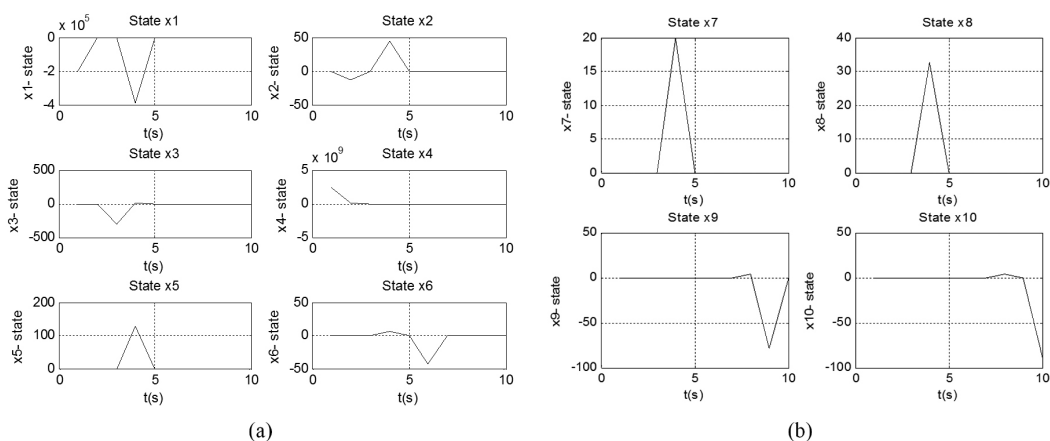


**Figure 5.** (a) Response of states x1 to x6 of the system modeled; (b) Response of states x7 to x10 of the system modeled.
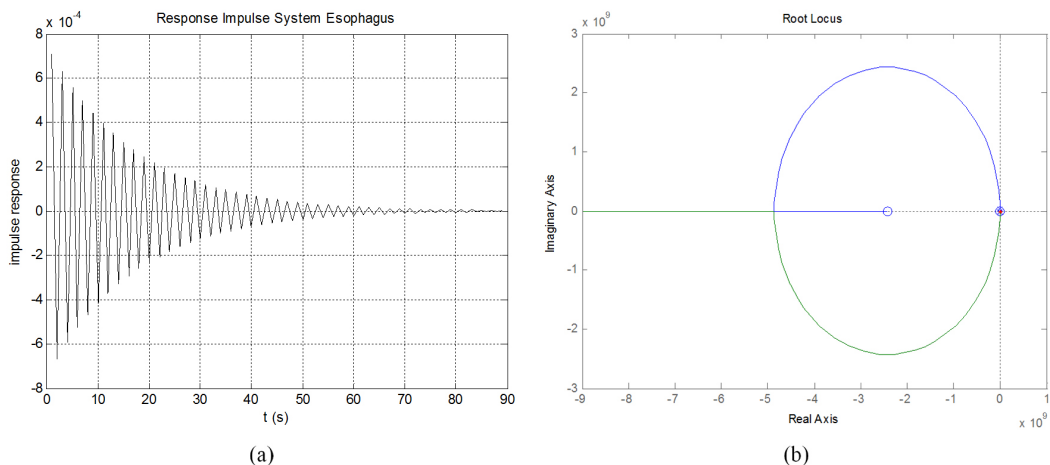


**Figure 6.** (a) Response of the system modeled to the impulse signal; (b) Root-Locus of the system modeled. Note that the eingevalues are in the left semi-plan providing stability to the system.
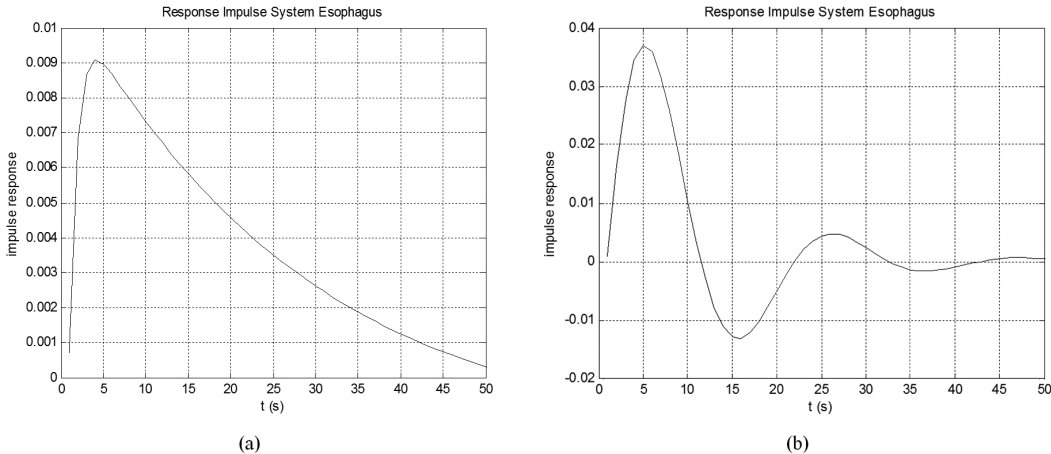
**Figure 7.** (a) Impulse response of the modeled system with ingestion of 5 mL of water. We considered the condition of uniform diameter throughout the extension of the esophagus; (b) Impulse response if the modeled system considering the ingestion of 5 mL of water and the use of EFC.

Furthermore, when the system is being excited by a continuous-time unit impulse, which is equivalent to a sip of water for 20 seconds, the system responds with a stable dynamic. At the beginning of the liquid intake there is a moderate transience, which represents the passage of resting pressure to working pressure.

When the upper esophageal sphincter area was reduced to a diameter of 1 cm, the dynamic behavior was changed since the system response was highly oscillatory and overshot to a greater degree. For this reason, it is possible to infer that the process of lowering food became slower; since the oscillation corresponds to a slower response of the system.

The descent speed of food makes it possible to conclude through analysis, according to (Rosa, 2009), that the inclusion of the EFC implies increasing resistance to passage of a bolus through the esophagus; as consequence, this changes the descent time of food and affects the process of human satiety.

The paper presented a mathematical model for understanding the dynamics of the human esophagus. We evaluated the relationship of the descent speed of the bolus with interference and the satiation of an individual. The method proposed allowed us to validate the hypothesis that the EFC creates a change in the fall time of the food, since after entering the esophagus it causes resistance to the passage of the bolus, the result of which is slower ingestion, which in turn affects the process of human satiety. Based on the absorption, or even the presence of food in the gastrointestinal tract, it contributes to the modulation of appetite and the regulation of energy.

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