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A cardiopulmonary system for a virtual patient

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Abstract

We present a simulation of a cardiopulmonary system. The simulation is used within a serious game to help for nurses education. It runs in real-time and can be easily modified to represent different illnesses. The system can adequately react when a nurse executes an unexpected action on the patient. The simulator uses a bottom-up design to model the cardiopulmonary system, using simple mathematical models and basic interactions to reproduce high-level and complex behaviors.

Introduction

Simulation is a good way to learn and practice in a safe environment. The simulation provides useful feedback to help students and trainees to learn from their mistakes. However in healthcare, most of the simulations and simulators require actors or mannequins (Issenberg et al., 2001; Morgan et al., 2006) to practice on. Since these simulations are expensive to use and can not be installed everywhere, it is hard for a student to practice anywhere else than schools and hospitals. Furthermore, most of these existing simulations for nursing education require the supervision of a technician or the use of a lot of parameters, which are often difficult to handle for an inexperienced user. Virtual simulations for nurses' training already exist (Hansen, 2008; Zary et al., 2006). However, most of them lack realism or tools needed by a teacher to provide useful and complete simulation for nursing students. To solve these major inconveniences, we propose a serious computer game coupled with a simulator that relies on interactions of simple components to reproduce complex behaviors. The model of the virtual patient is simplified and based on biological and physiological behaviors. It only specifies atomic parts of the complex system and the basic interactions between them. From these interactions, the required complex behavior emerges and can be studied. This innovative approach will help nurses taking charge of polytrauma patients at the hospital. Given the low frequency of certain clinical situations in critical care, the use of computer simulations to develop and maintain skills is very well-advised. This active and autonomous learning mode, exercised in a virtual world, will facilitate the transfer of skills in real-life situations. In the context of a shortage of clinical placement for nursing students, the computer simulation becomes a valuable tool within the reach of educational and health institutions to improve healthcare quality and patient safety.

The human body is a very complex system. Reproducing a perfectly accurate simulation of the human body would require a huge amount of computational resources and a perfect understanding of the underlying physiological processes. This is therefore an uneasy task if not, an impossible one. However, there are many efforts made to construct standards (Coveney et al., 2011; Clapworthy et al., 2008) and common parts (Ellaway et al., 2008) that could be used for a unified model of the human body. More realistic approaches, based on mathematical models like HumMod (Hester et al., 2011), are also developed. The mathematical approach of HumMod contains many variables and use complex formulas that represent the final behavior of the entire system. These models are very precise and require a good understanding of the underlying physiological processes. Researches in physiology and bioengineering are currently conducted to find these mathematical representations. One of the underlying objective of the presented simulator is to reproduce high level behavior without explicitly defining all possible interactions in the system with high level formulas used by these more classical mathematical models.

Most of the models developed for human body simulation use physiological and physical approaches to obtain adequate simulation (Attinger and Anné, 1966; MacIntyre, 2004). Some of them are slow to compute results, mainly due to the complexity of the formulas they used. Since the simulations must execute in real-time within a game engine, these models can not be used. The proposed model relies on such physiological and physical concepts. However, instead of representing complex interactions and using time-consuming computations, the system only uses basic physics formulas for on localized components, making it faster to compute.

In this paper, we present the cardiopulmonary system developed for the serious game used during the training of nurses. The next section describes the simulator and each of its subsystems. The third section shows some results of the simulator and a discussion about the simulator is presented in the fourth section.

Simulator description

Our current version of the simulator models the cardiovascular and the respiratory systems. Each system is modeled after its biological functions. The simulator runs in real-time and can thus be linked to a game engine in order to simulate an emergency room with an injured patient. Each of the modeled systems is a simplification of the reality but its behavior is consistent with the physiological response of its human counterpart.

The update process of the simulator relies on the game engine. The game engine updates the simulator periodically using a time step (Δt). Each system is updated accordingly to that time step by the simulator. For each update of a system, all its sub-components are also updated using this time step.

Body definition

The simulator relies on a XML file to describe the human body. The entire body description is decomposed into different systems, i.e. cardiovascular, respiratory, nervous, muscular, etc. This paper emphasizes only the description and the simulation of the cardiovascular and the respiratory system. Each system is viewed as a list of connectibles and a list of organs. Each connectible represents the media used for information transfer. Connectibles are grouped in subsets representing logical unit of information diffusion. For example, the blood vessels and how they connect to each other in the right arm will be specified as a subset for the cardiovascular system. In the cardiovascular system, the connectible are called blood vessels. In the respiratory system, they are airways and alveoli. Each connectible can be linked to other connectible to create a circuit. Each subset can also be linked to others, creating a more complex circuit for information diffusion. A connectible can be split into sections of equivalent volume. Each of these sections contain a part of the body fluid that moves into the connectible. For the circulatory system, it is a blood part. Each fluid part contains different metabolites (see the metabolites section for the definition). Fig. 1 illustrates the different compounds of a system for the circulatory system. The use of XML file to specify the different values used by the model have many advantages. Among others, it can be easily modified and it is simple to understand. Since the simulator is used for nursing education, the XML specification is also an easy mechanism to specify injuries to the patient and to create new scenario and cases to practice on.

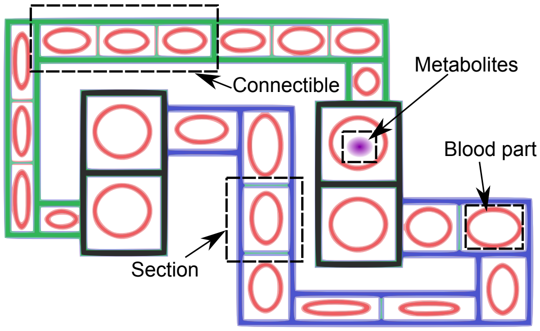

Figure 1: Simplification of the circulatory system to illustrate its different compounds. Each main color represents different subsets of connectible. The outermost bold rectangles are blood vessels (connectible). Inner rectangles are sections. Blood part (red circle) can contains different metabolites (purple circle). Blood vessels are linked together.

Circulatory system

One of the main system of a human body is the cardiovascular system. The blood flows through the body, diffuses nutrients to various organs and retrieves waste produced by cells. Most of the non-nervous signals of the body use the cardiovascular system to reach their area of action. In the simulator, a virtual bloodstream is used as a transporter and is composed of two circulation loops. The first one is the pulmonary loop. The blood flows from the right ventricle of the heart to the lungs and returns back into the left atrium. The second is the systemic loop. The blood flows from the left ventricle of the heart and returns back into the right atrium after passing through the different parts of the body. The blood flows in blood vessels, creating a delay between the emission of the signals (like hormones) and the start of the associated effect. At the beginning of the systemic circulation loop, the blood vessels, called arteries, divide into smaller vessels. They subdivide until reaching the capillaries bed, modeled as a large container of blood to simplify the simulation. In these capillaries, nutrients contained in the blood can diffuse to irrigated organs. The waste produced by the organs are diffused into the blood of the capillaries. The blood then continues its way back into other blood vessels, called veins. The veins merge together on their way back to the heart. These splitting and merging of blood vessels mix the content of the blood to ensure a better repartition of metabolites into all systems of the body. It is also mimicking very well the human circulatory system since blood vessels also split and merge in the same way. Fig. 2 shows the schematic view of the cardiovascular system.

Each blood vessel, as a connectible, is divided into sections containing different blood parts, each of them having some metabolites. When the simulator updates the cardio-

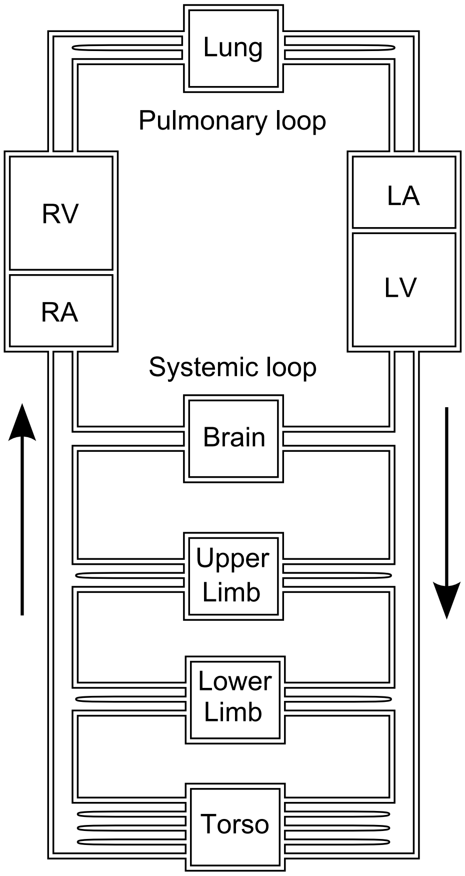

Figure 2: Schematic view of the cardiac model. LA and LV designate respectively Left Atrium and Left Ventricle. RA and RV designate respectively Right Atrium and Right Ventricle. The central boxes of the figure (i.e. Brain, Upper Limb, etc.) represent different connectible subset of the system. The subset contains arteries, veins and capillaries.

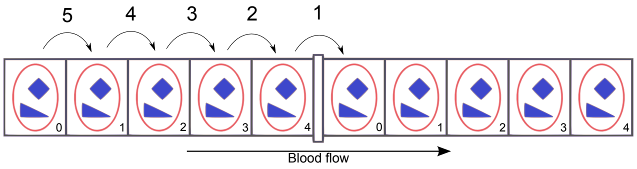

Figure 3: Schematic view of the update in blood vessels. The blood flows from left to right. In this example, each blood vessel contains five sections. Step 1 of the update process moves a certain quantity of blood from the last section of a vessel to the first section of all the next blood vessels, using Eq. 1. Then, step 2 to 5 move a certain volume of each other blood part to the next blood part in the vessel. This circulation of blood is executed in reverse order (from the last section to the first). It avoids transportation of new metabolites through all the blood parts of the blood vessels.

vascular system, each blood part flows through its vessel following the pressure gradient between that part and the next one in the vessel. In the simulation, each vessel is represented by a length (L) and a radius (r), thus modeled as a finite cylinder. This implies that each section of a blood vessel is also modeled as a cylinder of the same radius as the blood vessel but with a length of L/n for a vessel of n sections. To reproduce the pulsative flow of the blood, other simulations are based on the Windkessel effect, like Tsanas et al. (2009); Westerhof et al. (2009). The proposed simulator however relies on the standard Hagen-Poiseuille equation (Eq. 1) (Ganong et al., 2010; Marieb and Hoehn, 2010; Guyton and Hall, 2011) to calculate the volumetric flow rate (ϕ_i) in each blood vessel section i during a time step. The pulsatile work of the heart will impact the Eq. 1 by varying the pressure in a blood vessel section for a particular time step. The volumetric flow rate using the Hagen-Poiseuille equation is

$$\phi_i = \frac{\pi r_i^4 (P_i - P_{i+1})}{8 \eta L_i} \tag{1}$$

where r_i and L_i are respectively the radius and the length of the i^{th} blood vessel section in which the blood flows. P_i and P_{i+1} are the pressure of the blood in these sections and η is the dynamic viscosity of the blood. The length of a blood vessel section remains constant through the simulation. The pulsatile flow produced by the heart must be damped. In the human body, the elasticity of the blood vessel is responsible for this damping. To mimic this behavior in the simulator, we propose a model inspired by Hook's law of elasticity. The difference in volume between the actual volume of the blood part and the relaxed volume of the blood vessel section replaces the displacement value in Hook's law. An adjusted elasticity constant (k) is used, which can be specified for each blood vessel. The pressure P_i in the blood vessel section i is given by

$$P_i = \frac{k(V_i - W_i)}{2 \pi r_i L_i} \tag{2}$$

where V_i is the volume of blood in the i^{th} vessel section and W_i is the relaxed (initial) volume of that blood vessel section. The resulting change in pressure at each time step influences the volumetric flow rate given by the Eq. 1 of the next time step.

During a time step (Δt), all blood parts circulate throughout the sections of each blood vessel using the volumetric flow rate as explained previously. The new blood volume $V_i^{'}$ in each section i is represented with

$$V_i^{'} = V_i - (\phi_i - \phi_{i-1}) \Delta t \tag{3}$$

The blood part circulation is performed in reverse order. It is a design choice that required less memory than moving the blood parts in the way they flow. The simulator do not have to keep an entire copy of each blood parts until the end of the update pass. The Fig. 3 shows the different steps to flow the blood through each sections of blood vessels. Each transferred blood part contains the same metabolites, in the same ratio, as the initial blood part they came from. Since volume changes at each time step, the blood flow is constantly recalculated.

As explained, the capillaries are modeled as a large container. In human body however, capillaries are large network of very small blood vessels. This arrangement of blood vessels induces a great resistance to blood flow due to the small radius of these vessels. The Eq. 1 can be rewrited as

$$\phi_i = \frac{(P_i - P_{i+1})}{R_i} \quad with \quad R_i = \frac{8\eta L_i}{\pi r_i^4} \tag{4}$$

where R is the resistance to blood flow of the blood vessel. In the simulator, since the capillaries are modeled as a large container, the resistance of the container must be adapted to represent more accurately the resistance of a network of blood vessels. Each capillaries container has a number of sub-vessels (n). Each of them are identically modeled with a radius of 10 micrometers and a length proportional to the volume of blood of the entire capillaries container and the number of sub-vessel it contains. The model considers the sub-vessels in capillaries to be parallel, thus lowering the total resistance R_i, calculated with

$$\frac{1}{R_i} = \sum_{j=1}^{n} \frac{1}{R_j} \tag{5}$$

where R_j is the resistance in a sub vessel of the capillaries. Since all the R_j are identical, Eq. 5 can be simplified by

$$R_i = \frac{R_j}{n} \tag{6}$$

This model simplifies the blood flow in large and complex network of blood vessels in capillaries while keeping the physical incidence of their small radius on resistance.

To instill a pressure gradient to the bloodstream, the blood must be pumped. This role is devoted to the heart which is made of four parts. There are two atriums in which the blood arrives from the different circulation loops and there are two ventricles that pumped the blood out of the heart. The left atrium receives blood from the pulmonary loop while the right atrium receives it from the systemic loop. The simulated heart has also two group of self-polarizing cells, called sinoatrial node (SA node) and atrioventricular node (AV node). These nodes polarize and depolarize themselves to conduct the contraction of atriums and ventricles. For more details on heart nodes and their mechanisms, see (Guyton and Hall, 2011; Marieb and Hoehn, 2010). In the simulator, the polarization process goes through three different phases, as in reality. The first phase of the SA node is the pacemaker. The pacemaker is a slow increase of the polarization of the node. The pacemaker phase is followed by a rapid depolarization until the maximum is reached. This abrupt depolarization emulates the sudden increase of ions (charged metabolites) that transfer through the membrane of the cells in a real heart. The contraction of the atriums happens at the end of that phase. Finally, the third phase is the repolarization until the minimum value is reached and the cycle restart. During the pacemaker phase, the atriums relax and retrieve their original volumes. The AV node follows the same process. However, when the SA node reaches its maximum polarization value, the node sends a signal to the AV node. That signal disturbs the pacemaker phase of the AV node and initializes the rapid polarization. The contraction of the ventricles occurs when the polarization of the AV node reaches its maximum value. The relaxation of the ventricle follows during the pacemaker phase of the AV node. This depolarization/polarization, which is only an exchange of charged metabolites (mainly of sodium and potassium) between the membrane of the cells forming the heart, is simplified for the simulator.

This level of details for the heart's implementation, using polarization levels, allows a better control over its reaction to external stimuli. Instead of using a predefined timer to conduct the heart's beat and trying to find the right value for it in the simulator, the hormonal and neuronal systems can increase or decrease the different value of polarization in the nodes to change the behavior of the heart allowing it to beat faster or slower.

Respiratory system

The second simulated system is the respiratory system. This system is used to exchange the oxygen and the carbon dioxide between the body and the environment.

Like the human respiratory system, the virtual respiratory system has two main components, the lungs and the exterior environment. There are two lungs, and each of them is divided in different lobes. Each lobe contains alveoli in which the gases are exchanged with the blood in the capillaries. The lobes can be individually deactivated to simulate ill patients. The air enter the alveoli from the airways. The respiration control center is modeled as a timer. The rate of the respiration can be modified by changing the timer interval. It is in future plan to link this control center to a brain that will react to external stimuli, such as oxygen and carbon dioxide concentration as in real life. Fig. 4 shows the schematic of a lung in the system.

The air is modeled as an ideal gas (Eq. 7). And as a gas, it always fills all the available volume. The pressure P_{air} of the air depends on the volume V it fills, the temperature T in the lung, the quantity of gas (n) and the ideal gas constant R with the relation

$$P_{air} = \frac{nRT}{V} \tag{7}$$

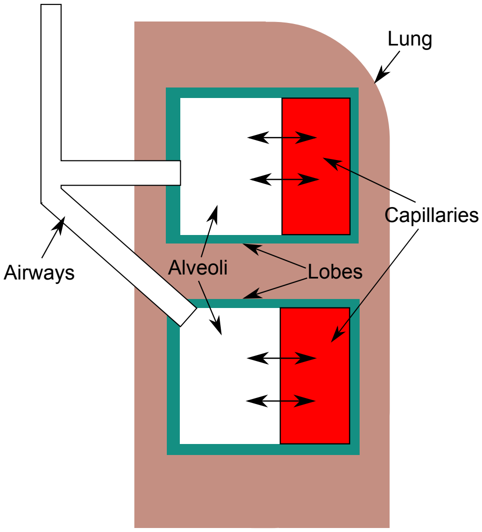

Figure 4: Schematic view of a simulated lung in the respiratory system. A lung is composed of lobes, each of them contains alveoli. The exterior environment is connected to the different alveoli using airways with one section. Capillaries of the circulatory system are linked to alveoli and exchange metabolites (i.e. oxygen and carbon dioxide) through gas diffusion.

The inspiration process increases the volume in the lung, while the expiration process decreases it. This difference of volume impacts the pressure of the air in the lungs, as explained by the Eq. 7. The air, as for the blood in the circulatory system, flows against its pressure gradient. But unlike the blood pressure, which depends of the elasticity of the blood vessels and the volume of blood it contains, the pressure of the air is calculated using the ideal gas equation (Eq. 7). In the simulator, the pressure of the exterior environment does not change as the respiration occurs. The air in the lung must always retrieve an equivalent pressure. Using Eq. 7, it is easy to find the amount of gas needed to balance the pressure between the lungs and the exterior environment. This amount of gas flows against the pressure gradient and balances the pressure in the lung at each time step.

The diffusion of gases between the blood and the alveoli of the lungs is driven by the partial pressure of these gases. However, each gas does not diffuse at the same rate. In the alveoli, all the gases composing the air are mixed together in a more complex gases mixture. This pressure of this mixture can be found using the Eq. 7. The partial pressure of each gas in the air can be calculated with the Dalton's law which states that the total pressure exerted by the mixture of non-reactive gases is equal to the sum of the partial pressures of each gases. For the air, the equation

$$p_i = P_{air}\frac{n_i}{n} \tag{8}$$

represents the partial pressure p_i of the i^{th} gas composing the air where n_i is the quantity in mole of this gas and n is the total amount of gases in the air. On the other hand, each gas dissolved in the blood has also a partial pressure. This partial pressure is calculated with the Henry's law stated as

$$q_i = \frac{n_i}{V}k_H \tag{9}$$

where q_i is the pressure of the i^{th} gas in the blood and n_i is the quantity of that gas in the blood. V is the volume of the blood part in which the gas is dissolved and k_H is the Henry's constant associated with the type of gas and the type of solution in which the gas is dissolved.

The diffusion of the gases takes place until the partial pressures in the air and in the blood are equal. Based on Fick's law of diffusion, the diffusion rate D_i of a gas i between the lung and the capillaries is

$$D_i = \frac{A(p_i - q_i)}{d}C_i \tag{10}$$

In this equation, C_i is the diffusion coefficient of the gas in the blood, A is the area of the blood vessel section that diffuses the gas, p_i and q_i are the partial pressure of that gas in the alveoli and in the capillaries and d is the distance of diffusion (Guyton and Hall, 2011). The quantity of gas Q_i added into the blood for a particular time Δt is

$$Q_i = D_i\Delta t \tag{11}$$

This diffusion process changes the respective partial pressure of oxygen in the blood and in the air of the alveoli. At the next time step, the diffusion rate changes accordingly and the cycle restarts upon equilibrium. For more information on gases diffusion in the human body, see Lumb (2010).

The respiratory system is responsible for the supply of new air into the body and for the expulsion of the exhausted one. In contrast with the circulatory system which is normally closed, the respiratory system is open. This particularity allows this system to be connected with different apparatus that provide breathable air or not. They are called the exterior environment. Normally, the respiratory system is connected to the atmosphere, composed at 78% of nitrogen and 21% of oxygen with the remaining being composed of many other compounds, like carbon dioxide and water vapor. The composition of this atmosphere influences the exchange of different gases in the lungs and in the body through the partial pressure of the composing gases. A higher concentration of oxygen in the air will increase the diffusion of this gas to the blood.

When the blood flows through the organs, it exchanges the oxygen and the carbon dioxide with them in a similar way than in the lungs. These exchanges change the partial pressure of these gases in the blood, resulting in continuous exchange when it passes through the lungs. The exchange of gases in the organs follows the same principles as in the lungs with the equilibrium of partial pressures. The major difference is that the partial pressures of the gases in organs are found using the Henry's law (Eq. 9) instead of Dalton's law (Eq. 8). It is because the gases in organs are dissolved into the cells' fluids.

Metabolites

All biological elements are called metabolites. Thus, every molecule that use the bloodstream or the pulmonary airways to circulate is considered to be a metabolite. It represents the oxygen, the carbon dioxide as well as the sodium, the potassium, the enzymes, the hormones and any other elements used by a system of the body. Like in human body, every blood parts, organs' fluid and air parts can contain metabolites. Instead of representing all the individual instance of a metabolite, like all atoms of oxygen dissolved in the blood, each metabolite is represented with a quantity representing the amount of individual instances. This simple representation of each set of metabolites in blood parts simplify the calculation in the different systems of the body. The pressure, the volume and the concentration, for example, can easily be found for a particular metabolite in a single blood part. The advantage of grouping all instances of the same metabolite limits the memory and the time needed to update all the systems. Furthermore, this simplification has only a small impact on the system, since it represents only a part of all instances of that metabolite in the whole body. The subdivision of the blood part and the air part allows precise control and limits actions to a specific section.

Results

The developed system must be realistic enough to be used as a simulator for nurses education. The global behavior of the system must represents the way the human body behave in similar circumstances. The first experiment validates the behavior of the heart and the change in pressure into the bloodstream as the heart beats. It shows that cutting blood vessel to represent injuries has an impact on pressure. The second experiment validates the effect of the gases composing the atmosphere on the bloodstream. The experiment also demonstrates the effect of a ill lung to the respiratory system. The system needs 3 or 4 heart beats to stabilize at the beginning of a simulation.

The Work of the Heart

The heart acts like a pump. It contracts and relaxes periodically. The effect of that pump is a continuous increase and decrease of the blood pressure in the arteries. The standard values of pressure for a healthy person are between 120 mmHg (or 16 000 Pascals) at the maximum and 60 mmHg (or 10 700 Pascals) at the minimum (Chobanian, 2004). These values represent the pressure in the blood vessels. It is the force exerted by the blood on a blood vessel wall. The

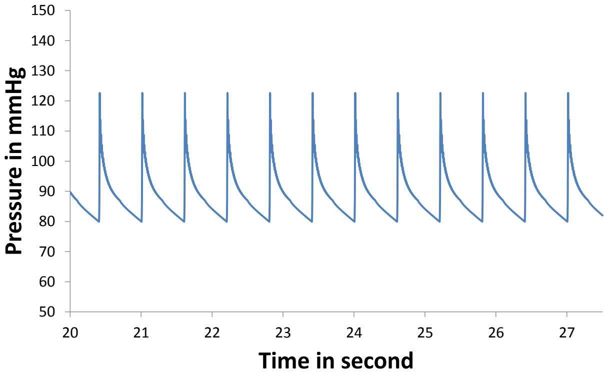

Figure 5: Pressure in the simulated aortic artery, at the exit of the heart. The pressure oscillates between 122 mmHg and 80 mmHg, which is in standard range for a main artery.

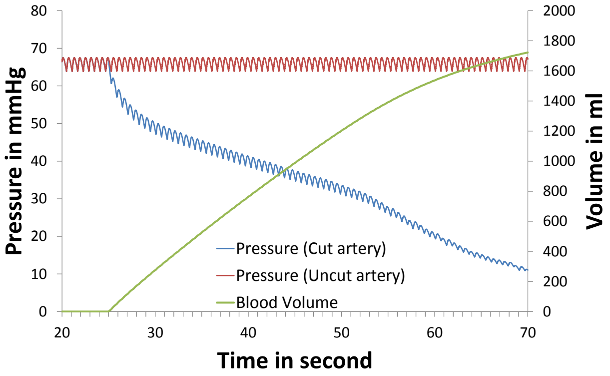

Figure 6: Blood pressure in a simulated artery that follows a cut. The green curve shows the volume of blood that has escaped through the cut. Red curve is the pressure in the artery when no cut is present in the system. Blue curve is the pressure in the same artery when a cut is present.

Fig. 5 shows the pressure of the blood in the simulated aortic artery at the exit of the left ventricle. The pressure rises when the heart contracts and decreases when the blood flows out of the heart.

To simulate an injured patient, the cardiovascular system allows blood vessels to be cut. The Fig 6 shows the effect of a cut at the end of the simulated artery network, before entering smaller capillaries vessels. Standard pressure in these arteries is lower since resistance and elasticity damped the pulse (Marieb and Hoehn, 2010). The volume of blood that leave the blood vessel is shown as well as the corresponding blood pressure in the next connected blood vessel. This cut to the artery should be deadly if no action is taken rapidly to mitigate the problem. The virtual patient rapidly loses blood, leading to a decrease in its pressure, and possibly death. The cut is considered open and the blood escap-

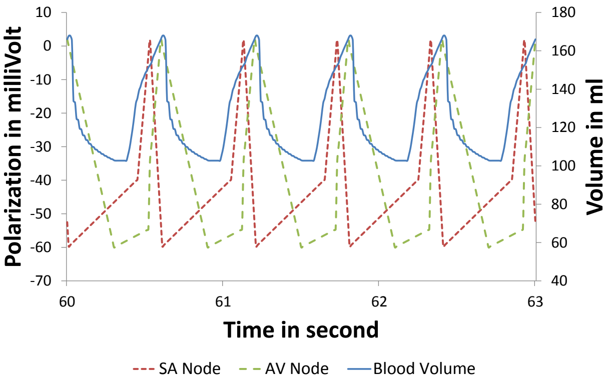

Figure 7: Blood volume variations of the left simulated ventricle over time. The first increase in blood represents the blood flowing from the left atrium to the left ventricle following the pressure gradient. The second increase occurs when the left atrium contracts, pushing the blood into the ventricle. The following decrease occurs when the ventricle contracts and expulses the blood into the aorta.

ing from the system exerts no pressure on the blood vessels or other organs. If the cut was modeled as a hemorrhage, the blood escaping the system would exert a pressure on the blood vessels, slowing the blood loss.

Another interesting feature of the simulator is the possibility to reproduce hypertension behavior. Results show that increasing the elasticity constant of a blood vessel, thus stiffening it, increases the maximum blood pressure in the neighboring vessels. Futhermore, the peak of the blood pressure in blood vessels occurs later in time with less elastic vessels, as explained in Mitchell (2006).

As explained previously, the heart is modeled as a pump with polarizations threshold. The pumping effect of the atriums and ventricles influences the volume of blood in the heart. The Fig. 7 shows the variations of the blood volume in the left ventricle of the simulated heart in relation with the polarization phases of the SA and AV nodes. The atriums contract when SA node reaches its maximum polarization value. The contraction of ventricles occurs shortly after when AV node reaches its own maximum polarization. The variation in blood volume for the ventricles is similar to the reality (Marieb and Hoehn, 2010).

The Influence of the Air

Air composition influences the gas exchange in the human lungs. At the top of a mountain, the air pressure is lower than at sea level, which influences the partial pressure of oxygen. In the simulator, there is also a difference of partial pressure for the oxygen in the blood when the exterior atmospheric pressure changes. At sea level with standard atmospheric pressure (101 325 Pascals), the partial pressure of oxygen in the simulated blood is about 160 mmHg (104 mmHg in reality) after passing the alveoli of the lungs. At 2000 meters of altitude (70 000 Pascals), the partial pressure of oxygen in the blood is about 110 mmHg (71.93 mmHg in reality) after passing the alveoli of the lungs. The difference of partial pressure of oxygen between the simulated blood and the reality is mainly due to the absence of water vapor in the air of the simulated lungs which increases the partial pressure of oxygen, following Eq. 8 (Marieb and Hoehn, 2010). The absence of water vapor simplifies the process of air exchange between the exterior environment and the simulated lungs. However, the results show clearly that a difference in initial atmospheric pressure impacts the system.

Discussion

The goal of this work is to reproduce the behavior of a cardiopulmonary system. This simulator is used within a serious game for the training of nurses. One of the primary requirements of the system is a good representation of external and internal physiological processes. The system does not represent the exact reality. However, it must be realistic enough at a high level to create an immersive environment for the nurse. The presented simulator is based on simple mathematical concepts of chemistry and physics to mimic the basic interactions and behaviors of this complex system.

The presented approach, using a bottom-up design, relies on the principle of emergence to reproduce the complex interactions needed for this kind of simulation. This is in contrast with more standard approaches used in the video games industry. In a game, simulation and artificial intelligence often use finite-state machines. They are easy to define, the interaction between each component is clear and it can normally represent most of the desired behavior. However, relying on this model for a human body simulation has many disadvantages. First, there are many systems interacting together, thus complexifying the machine and increasing the chance to forget transitions when designing it. Second, this finite-state machine would required a huge amount of memory space and adding another system in the body simulation would require a lot of efforts to connect it with the others. Finally, every interactions on the model must be planned in the design stage, which are every actions and mistakes made by a nurse in training using the simulator. Naturally, predicting every mistakes and the order in which they will be made is a virtually impossible task. All these concerns have led us to create a simulator based on simple components interacting together so that complex behaviors can emerge.

The presented model is based on the subdivision of the entire system in logical units. The approach can be related to multi-agents system, where each part of the system executes its own job and send messages to other units to influence them. The model used for the simulator sends messages mainly through the bloodstream. An interesting effect of this message sending is the delay that occurs between the time a message is sent (i.e. an hormone is produced and released in the blood) and the time it reaches its zone of effect (i.e. when it binds to receptors to activate functions).

Again, the main advantage of using this kind of approach is the ability of the system to react automatically and adequately to the numerous possible actions of the nurses. When the simulator is in an unstable state, i.e. the virtual patient has injuries, the nurse in training must execute actions to stabilize it. When the nurse makes an action, the simulator must react adequately and it must continue running. The result of the action will impact the patient, thus reflecting what would happen in reality.

Mathematical models act in the same way as our approach. There is no need to plan every mistakes made by a nurse in the system. Actions will impact the formulas to provide new outputs. However, these models, even if they are extremely efficient and complete, can often be difficult to be divided and modeled as independent sub-system.

Modeling complex systems with simple components similar to multi-agents systems is an interesting idea that allows modularity, simplicity and speed of execution. The simpler formulas used in the presented simulator represent only basic physical interactions and are used to construct more complex behaviors. In a simulator that must reproduce global behavior instead of particular physiological principles, this modularity and simplicity of configuration offer a great advantage for both the developer of medical scenarios and the nurse in training.

Conclusion

We describe a model of a cardiopulmonary system that is inspired by biological principles. The resulting behavior of the simulator corresponds to the actual behavior of a human body, thus allowing the simulator to be used for nurses' training. The decomposition into small and simple components to see the emergence of complex behaviors is an interesting way to model the problem. The teacher can specify injuries and illness to a patient, thus simplifying the creation of new medical scenarios.

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