Simulation for enhancing e-Learning environments: a software for teaching heart-lung interaction to medicine students

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***Abstract*— Heart-lung interaction must be analyzed while assisting patients with severe respiratory problems or with heart failure in intensive care unit. Such patients can be assisted by mechanical ventilatory assistance or by thoracic artificial lung.**

This paper presents an e-Learning environment aiming at teaching the interaction of cardiovascular and lung systems to medical students. Such an environment was experimented during a training course given to students of the School of Specialization in Cardiology at the Department of Cardiovascular, Respiratory, Nephrological, Anesthesiological and Geriatric Sciences held at 'Sapienza' University in Rome.

The training course employed CARDIOSIM©, the numerical simulator of the cardiovascular system. Such simulator is able to reproduce pathophysiological conditions of patients affected by cardiovascular and/or lung disease. The simulator implements several different cardiovascular pumps in order to assist one or both ventricles in parallel or in series. Thoracic artificial lung assistance was applied in parallel and hybrid mode to show the different effects produced on left (right) ventricular end diastolic (systolic) volume, cardiac output, mean pulmonary arterial pressure, mean left atrial pressure, mean systemic venous pressure and the value of the area of coronary blood flow-aortic pressure loop (CBP-AoP). The results presented here are consistent with those presented in the literature.

Finally, the paper discusses the benefit of employing a software simulator to enhance the performances of an e-Learning environment.

We also believe that not only a simulation software, but also an ontology-based modelling of the relevant concepts involved in the e-Learning domain is a valid approach in order to reuse an environment in other domains or for other students' profiles (e.g. general practitioners, anesthesiologists, nurses).

I. INTRODUCTION

Heart-lung interaction must be analyzed when patients with heart failure or with severe respiratory problems are assisted in Intensive Care Cardiac Unit. Some pulmonary diseases can be the result of haemodynamic pathology, most notably an increase in pulmonary vascular resistance. In these cases the right ventricle (RV) is overloaded and cardiac output is reduced to problematic levels. In many pulmonary diseases, both gas exchange and haemodynamic disturbances are present to some degree. Therefore an accurate analysis of the heart-lung interaction must be done in those patients with severe respiratory problems or with heart failure [1].

Chronic respiratory failure or severe pulmonary infections can be treated using thoracic artificial lung that do not use a pump, but rather can be attached to the natural lung (NL) in series, in parallel or in hybrid mode [2],[3].

Cardiovascular software simulator can be a useful tool for studying and training in the management of mechanical circulatory and ventilatory devices [4].

During a training course held for students of the School of Specialization in Cardiology at the Department of Cardiovascular, Respiratory, Nephrological, Anesthesiological and Geriatric Sciences, "Sapienza" University of Rome, heart-lung interaction was studied when thoracic artificial lung assistance was applied. In order to perform the training course the numerical cardiovascular simulator (CVS) CARDIOSIM© was used.

In the next paragraph we present the software simulator of the cardiovascular and lung systems (CARDIOSIM©) [5],[6] usable to train cardiologists, anaesthesiologists, nurses and medical students.

II. THE CARDIOVASCULAR SIMULATOR SOFTWARE

The software simulator, developed at the Institute of Clinical Physiology (National Research Council), is able to reproduce phatophysiological conditions of patients affected by cardiovascular and/or lung disease [7],[8]. In the simulator we implemented many different cardiovascular pumps to assist one or both ventricles in parallel or in series way [7],[8],[9]. The blood pump implemented can reproduce pulsatile or continuous flow.

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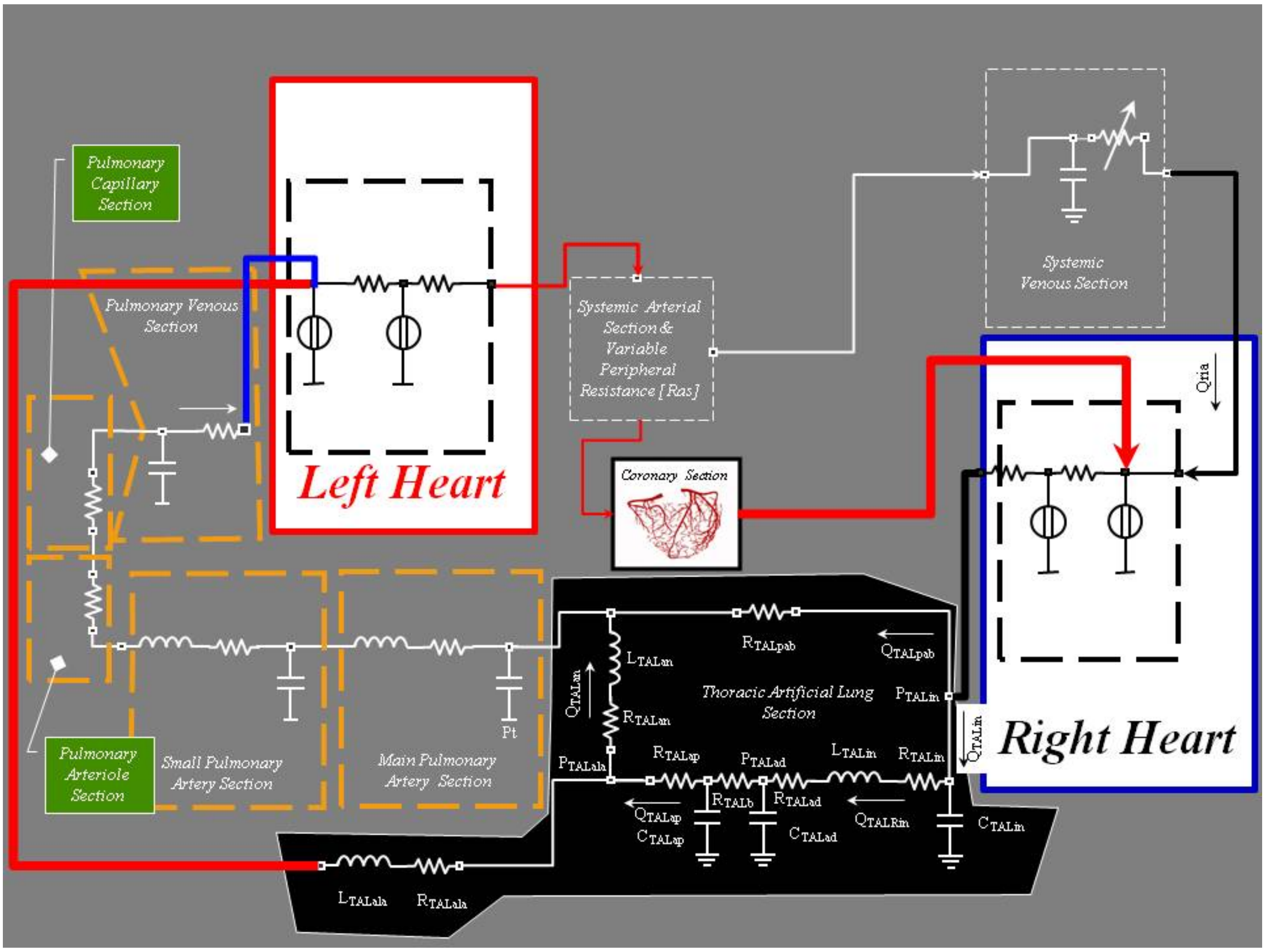

Figure 1. Electrical analogue of the cardiovascular simulator and of the thoracic artificial lung (TAL). The cardiovascular model is divided in different sections: left (right) heart, systemic arterial section, systemic (pulmonary) venous section, pulmonary aortic sinus and artery sections, pulmonary arteriole and capillary sections and coronary section. Left (right) heart consists of left (right) atrium and ventricle. The behavior of atria and ventricle is reproduced using variable elastance model. TAL can be connected to natural lung in series, in parallel and in hybrid mode.

The assistance to the lung is realized implementing a thoracic artificial lung (TAL) that can be connected to the NL in parallel, in series and in hybrid mode. The software has a graphical and a numerical interface which shows the instantaneous waveforms during the cardiac cycle and the mean values of pressures, volumes and flow.

In order to study the heart-lung interaction in presence of TAL, by haemodynamic point of view, starting by baseline conditions, the effects of different TAL assistances (in parallel and hybrid mode) were reproduced by changing TAL compliances [2],[10] and resistances, in presence of different pulmonary vascular resistance values.

The results obtained during a training course held for students of the School of Specialization in Cardiology at the Department of Cardiovascular, Respiratory, Nephrological, Anesthesiological and Geriatric Sciences, University "Sapienza" of Rome, are in accordance with literature data.

A. The cardiovascular model

CARDIOSIM© was developed at the Institute of Clinical Physiology [5] in collaboration with the National Institute of Cardiovascular Research. It is a cardiovascular simulator that can be assembled in different ways. The configuration used during the course held for the students of the Department of Cardiovascular, Respiratory, Nephrological, Anesthesiological and Geriatric Sciences, University "Sapienza" of Rome, is reported in Fig. 1.

The electrical analogue of the cardiovascular system (represented in Fig. 1) shows the left and right ventricles (atrium), coronary section, systemic arterial and venous sections, main and small pulmonary artery sections, pulmonary arteriole and capillary sections, pulmonary venous section and thoracic artificial lung section.

The behaviour of both ventricles, atrium and septum, were reproduced by means of variable elastance model [11],[12],[13],[14]. The atrial septum is assumed to be rigid. This representation allows to reproduce the Starling's law of the heart [15]. The different sections of the circulatory network was implemented using lumped parameter models:

a) Systemic arterial section was reproduced using a modified windkessel with a variable peripheral resistance [9],[16];

b) Systemic venous section was implemented by compliance and variable resistance [6],[16],[17].

c) Main and small pulmonary artery sections were reproduced by RLC model [2],[18],[19].

d) Pulmonary arteriole and capillary sections were modelled by a single resistance [2].

e) Pulmonary venous section was reproduced by RC element [18],[19].

f) The behaviour of the coronary network was implemented by lumped parameter model based on the intramyocardial pump concept [20],[21],[22],[25].

B. *The thoracic artificial lung model cardiovascular model*

The electrical analogue of the thoracic artificial lung is shown in Fig. 1. TAL assistance can be connected to NL in “series mode” or “parallel mode” or “hybrid mode” (Fig. 2). In “parallel mode” the blood flow is routed from the pulmonary artery through the TAL and then returned to the left atrium. This configuration reduces impedance of the TAL and natural lung system. In “series mode” the blood flow is routed from the proximal pulmonary artery through the TAL and then back to the distal pulmonary artery, where the blood then flows through the NL and finally back to the left atrium. In “hybrid mode” the blood flow is routed in part to the NL through the TAL and in part to the left atrium through the TAL. Studies on parallel TAL attachment have shown the decrease of pulmonary system impedance and the increase of cardiac output, while in series TAL attachment increases pulmonary system impedance and decreases cardiac output [24].

In CARDIOSIM© TAL was implemented using a lumped parameter model (Fig. 1). Five parameters (R_{TALap}, R_{TALad}, L_{TALap}, L_{TALad} and R_{TALb}) were used to model the TAL. Hybrid TAL configuration is realized connecing the pulmonary circulation through the resistance (R_{TALpab}) and linking the left atrium through the RL elements (R_{TALala} and L_{TALala}). In-series mode was implemented setting the resistances R_{TALpab} and R_{TALala} to infinity value. Parallel TAL configuration was realised setting the resistance R_{TALan} to infinity value.

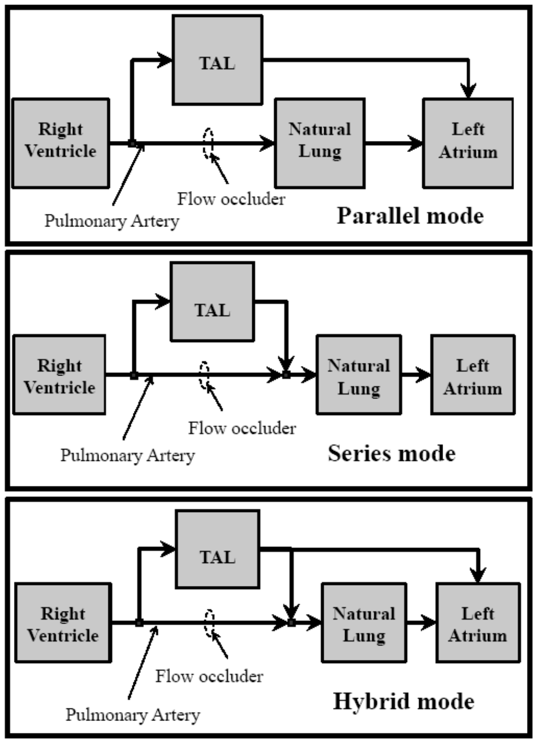

Figure 2. Thoracic artificial lung attachment: parallel, series and hybrid mode.

III. Experimental method

The training course on the interaction of cardiovascular and lung systems was held for 25 students of the School of Specialization in Cardiology and consisted in 8 two-hour classes. During such classes cardiocirculatory pathological conditions of patients admitted to the Department have been reproduced. By using the numerical simulator, the students simulated various drug therapies aimed at improving the patients’ cardiocirculatory conditions [25]. The training course took into account also pathological cardiocirculatory conditions which, in order to be solved, need: ventricular assist devices (VADs) [6],[8],[9], intra-aortic balloon pump (IABP) [26], biventricular pacemakers [7], mechanical ventilatory assistance [8],[9] and so on.

In the following we describe a case study carried out during the seminars. We reproduced a pathological condition that produced the following effects on the haemodynamic variables: an increase of right ventricular end systolic volume, an increase of right ventricular end diastolic volume and an important increase of pulmonary arterial pressure.

Starting by these circulatory conditions (baseline conditions), the experiments were divided in different steps. In the first step parallel TAL assistance was applied, and the pulmonary arterial peripheral resistance was set to Rap = 240 [$g \cdot cm^{-4} \cdot sec^{-1}$], TAL compliances were set to C_{TALin}=1.5 and 0.4 [ml/mmHg] and C_{TALad}=C_{TALap}=2.0 and 0.1 [ml/mmHg].

In the second step the same simulations were performed setting Rap = 120 [$g \cdot cm^{-4} \cdot sec^{-1}$].

Finally the same simulations were reproduced for the hybrid TAL assistance.

In all simulations the analyzed variables were: left ventricular end diastolic volume (LVEDV), left ventricular end systolic volume (LVESV), right ventricular end diastolic volume (RVEDV), right ventricular end systolic volume (RVESV), cardiac output (CO), mean pulmonary arterial pressure, mean left atrial pressure, mean systemic venous pressure and the value of the area of coronary blood flow-aortic pressure loop (CBP-AoP) [14],[25]. The mean values were calculated during the cardiac cycle.

IV. RESULTS

Starting from baseline condition described in the previous section, the effects produced by TAL assistance applied in parallel and hybrid mode is shown in Fig. 3. Panel A shows the percentage changes obtained staring from baseline condition and applying parallel TAL assistance. The simulations have been performed setting Rap=240 [g·cm^{-4}·sec^{-1}]. TAL assistance increase LVEDV and LVESV but reduces RVEDV and RVESV. The reduction of RVEDV and RVESV allows the right ventricular pressure-volume (P-V) loop to move to the left in the pressure-volume plane [23].

According with literature data, parallel assistance produces an increase in cardiac output [24]. A reduction of mean pulmonary arterial pressure and an increase of CBF-AoP area have been produced by parallel TAL mode. Panel B show the effects induced by hybrid TAL assistance when peripheral resistance was set to 240 [g·cm^{-4}·sec^{-1}].

In both panels we report results obtained for different values of TAL compliances. The percentage changes induced by hybrid TAL assistance are lower than those produced by parallel assistance. Only in the case of the mean pulmonary arterial pressure there is a percentage reduction which, in case of hybrid assistance, is greater (about 40%) than in case of parallel assistance (20-30%). Finally it is possible to observe that, in the described condition, TAL assistance increase the mean left atrial pressure, as described in literature [27].

Fig. 4 shows the evolution of the left and right ventricular P-V loop, when, starting from a baseline condition, TAL assistance was applied in parallel mode. By analysing the figure, it is possible to observe how the left ventricular pressure-volume loop moves to the right (increasing LVEDV and LVESV) in the P-V plane (upper window) from position A (baseline condition) to position B (assists condition). The right ventricular P-V loop (in lower window) moves towards the right side in the P-V plane from position A (baseline condition) to position B (assisted condition). This effect produces a reduction of RVEDV and RVESV and an increase of right ventricular efficiency.

Fig. 5 shows the percentage changes of some haemodynamic variables when the pulmonary arterial peripheral resistance was set to 120 [g·cm^{-4}·sec^{-1}]. Panel A shows the percentage changes when parallel TAL assistance was applied. The trend presented in Fig. 5 (panel A) is the same presented in Fig. 3 (panel A), the percentage changes are more pronounced in this second figure. The percentage change in cardiac output seems to be the same regardless of the value of the pulmonary arterial peripheral resistance. Panel B of Fig. 5 shows, for hybrid TAL assistance, a reversal of the trend (with

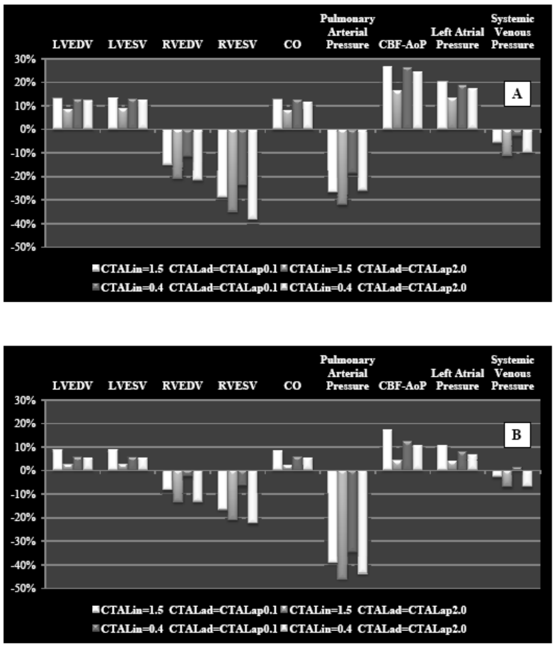

Figure 3. Percentage changes of haemodynamic variables with respect to baseline conditions, calculated when parallel TAL assistance (panel A) and hybrid TAL mode (panel B) were applied. Different simulations are performed setting C_{TALin}=1.5 and 0.4 [ml/mmHg] and C_{TALad}=C_{TALap}=0,1 and 2.0 [ml/mmHg]. The simulations have been performed setting Rap=240 [g·cm^{-4}·sec^{-1}].

respect to panel B, Fig. 3) in the percentage changes in some variables in correspondence with some combinations of TAL compliances value. This phenomenon occurs in LVESV, LVEDV, RVESV, RVEDV, cardiac output, mean left atrial pressure and in CBF-AoP area.

The CO is one of the variables on which researchers focus attention during TAL assistance. Fig. 6 shows the percentage changes (respect to baseline conditions) of CO when TAL assistance was applied in different mode, with different Rap values and with different TAL compliances.

Panel A (Rap=240 [g·cm^{-4}·sec^{-1}]) emphasizes that, in the case of parallel assistance, independently of the values assumed by TAL compliances, cardiac output is more or less double with respect to hybrid assistance. Panel B (Rap=120 [g·cm^{-4}·sec^{-1}]) shows that parallel TAL assistance produces an increase in CO, whereas hybrid assistance can produces a reduction in CO.

V. CONCLUSIONS AND FUTURE PROSPECTS

An e-Learning environment can take profit from the employment of a software simulator such as CARDIOSIM©.

Among the advantages of using a simulator, we have to consider that the same pathophysiological conditions can be replicated several times by the students without any damage for the virtual patient.

In particular, it is possible to simulate:

- ✓ Drug subministration and their effects on haemodynamic variables
- ✓ Circulatory mechanical and ventilatory support devices

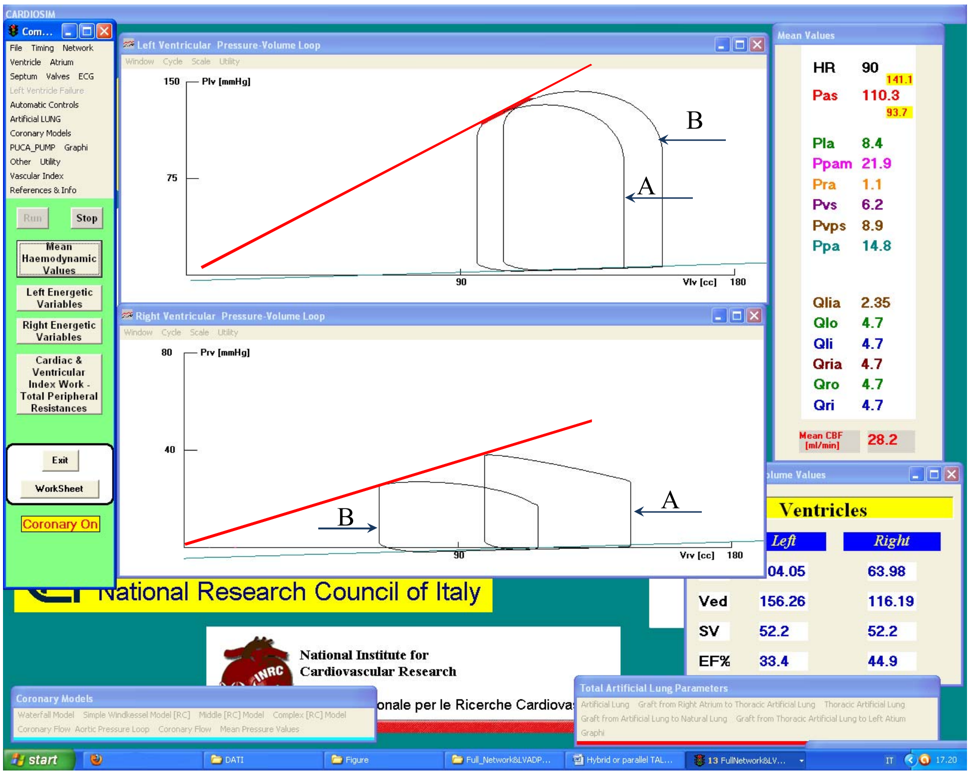

Figure 4. Screen output produced by CARDIOSIM© software. Starting by baseline condition (loops A) TAL parallel assistance was applied by setting C_{TALin}=1.5 and C_{TALad}=C_{TALap}=2.0 [ml/mmHg]. Upper (lower) window shows left (right) ventricular P-V loops. Loops A (B) reproduce baseline condition (TAL assisted condition). Right upper column shows mean pressures and flows calculated during the cardiac cycle. HR is the heart rate. Right lower column shows left and right ventricular end systolic and end diastolic volumes. SV is the stroke volume. EF% is the ejection fraction. Left column is the command column. In both simulations Rap was set to 240 [g·cm^{-4}·sec^{-1}].

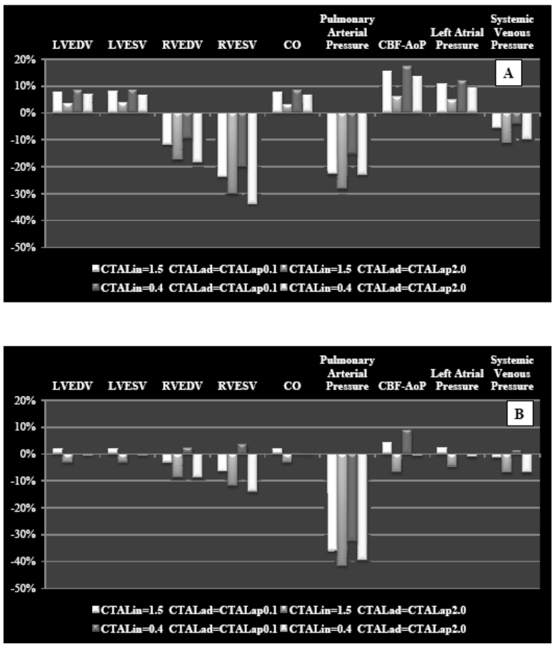

Figure 5. Percentage changes of haemodynamic variables with respect to baseline conditions, calculated when parallel TAL assistance (panel A) and hybrid TAL mode (panel B) were applied. Different simulations are performed setting C_{TALin}=1.5 and 0.4 [ml/mmHg] and C_{TALad}=C_{TALap}=0,1 and 2.0 [ml/mmHg]. The simulations have been performed setting Rap=120 [g·cm^{-4}·sec^{-1}].

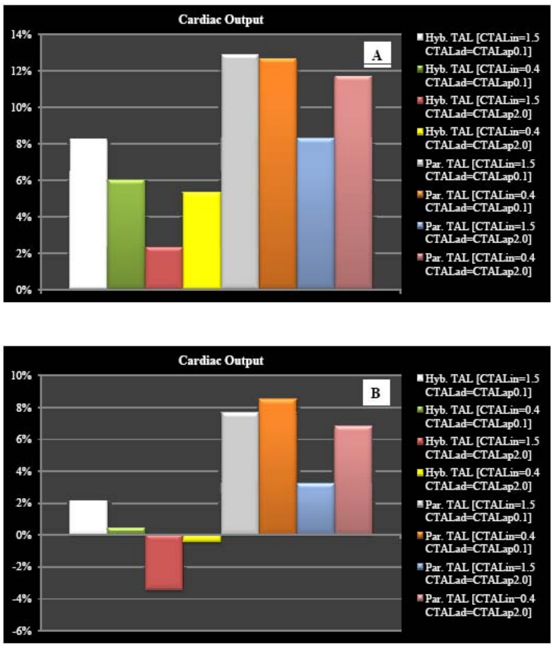

Figure 6. Percentage changes of CO with respect to baseline conditions, calculated when parallel Rap=240 [g•cm-4•sec-1] (panel A) and Rap=120 [g•cm-4•sec-1] (panel B). Different simulations are performed when TAL assistance was applied in parallel and hybrid mode. CTALin was set to 1.5 and 0.4 [ml/mmHg]. CTALad and CTALap were set to 0.1 and 2.0 [ml/mmHg].

- ✓ The effects of choosing, configuring and activating one of such devices
- ✓ The effects of possible adjuments of device parameters

Currently, the e-Learning tool we implemented is used in a local environment in a traditional face-to-face interaction between teachers and students. In the future, we plan to extend the e-Learning features in a telematic virtual environment by means of an internet based platform.

We also believe that not only a simulation software, but also an ontology-based modelling of the relevant concepts involved in the e-Learning domain is a valid approach in order to reuse an environment in other domains or for other students' profiles (e.g. general practitioners, anesthesiologists, nurses).

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