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A web-based training simulator of clinical hyperbaric chamber

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This work describes an innovative simulator for clinical hyperbaric chambers that addresses critical training gaps in hyperbaric medicine. The system provides medical and technical personnel with a risk-free environment to develop essential operational skills without endangering patients or costly equipment. The simulator employs a dual-module architecture with web-based accessibility, intuitive controls for realistic chamber operation, and robust administrative capabilities. To evaluate the effectiveness of the simulator in the training process, we conducted a pilot study with clinical professionals. This study demonstrated significant improvements in procedural proficiency and emergency response capabilities, with participants showing measurable skill enhancement after simulator-based training sessions. The preliminary quantitative assessments revealed high educational value of proposed simulation software. This technological advancement represents a substantial contribution to hyperbaric medicine education, supporting both initial training and ongoing competency maintenance for clinical and technical operators in this specialized medical field.

Keywords Hyperbaric medicine, Clinical hyperbaric chambers, Simulation, Modelling, Medical education

Simulation is now a topic of debate in numerous disciplines, from mathematical engineering sciences to psycho-pedagogical studies, from the field of research to theories of management, as well as involvement in the film industry and the arts in general[1,2]. Simulation refers to a technique or methodology for artificially reproducing the conditions associated with a phenomenon. In other words, it is the attempt to reproduce, also thanks to technology, an environment or system, whether real or imaginary, the behavior that is activated in that system and to study its changes over time. Documented benefits include improving patient safety and reducing healthcare costs by improving the skills of healthcare workers[3,4]. In this context, hyperbaric treatment, considered an emergency condition, requires clinical management of the hyperbaric exposure period requiring both individual and team clinical skills[5–7].

The hyperbaric chamber is a physical space, present in the most modern hospitals and medical clinics, inside which an individual can breathe in pure oxygen or oxygen-rich compressed air at pressure levels significantly higher than those found in the environmental air[8]. The reason for the use of such high pressure in hyperbaric chambers is the fact that it provides the human body with greater accessibility to oxygen. The treatment, known as "hyperbaric oxygen therapy (HBOT)", consists of administering 100% oxygen at higher pressure, raising oxygen levels in the blood and tissues[9,10]. This treatment is indicated in a variety of medical conditions, including decompression sickness, gas embolism, severe anaemia, carbon monoxide poisoning, burns, compartment syndrome, brain abscess, and necrotizing infections[11] In particular, HBOT is indicated in the healing of chronic wounds, those related to diabetes or radiation injuries, by increasing the concentration of oxygen in the blood and tissues. It is also useful for conditions such as carbon monoxide poisoning and severe anaemia, reducing inflammation and oedema in the tissues involved in the injury, increasing the infection-fighting capacity of white blood cells and aiding in the treatment of infections[12,13].

The simulation of a hyperbaric chamber offers advantages in initial training and in maintaining acquired skills over time[14,15]. Education and training often conflict with the overload of clinical routines, so it is useful and advantageous to carry out simulation activities aimed at improving the learning curve, thus reducing the time spent on the real system. Simulation offers undoubted advantages in all those situations that are difficult or dangerous to realize, such as incandescence with the consequent containment and inhibition measures. Healthcare workers involved in the provision of HBOT must possess both technical and non-technical skills. In many countries, training to become a certified hyperbaric health professional includes only didactic lectures[7]. Training for initial certification usually does not include simulation-based training and, to date, there is no

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recognised simulation course in hyperbaric medicine. Based on evidence from other medical areas that support and promote the impact of simulation, it is conceivable that a simulation-based tool in hyperbaric medicine could improve practitioner performance both individually and as a team, with benefits for patients as well[16,17]. Thus, starting from the fact that simulation is an effective training modality that is increasingly being adopted in all fields of medicine, the paper illustrates the characteristics of a simulation software, developed at the Institute of Clinical Physiology of the National Research Council in Pisa, relating to the simulation of a hyperbaric chamber for clinical use, showing also some preliminary results about the effectiveness of the simulator in the training process.

Previous work in the field of simulation

Previous studies in the field of simulation has explored its effectiveness in enhancing decision-making, improving technical and non-technical skills, and supporting training in complex or high-risk environments across various domains, including healthcare, aviation, and emergency management[18,19]. The fundamental characteristic of simulation is therefore to be able to verify in real time the consequences of the actions of the subjects involved[20]. In the field of professional training, simulation is one of those alternative training methods that aim to anticipate the transfer of expert knowledge before it enters the work process or in other cases accompany it throughout the professional career[21]. The use of simulation to reproduce standardized models and rules represents *a de facto* standardization of the work experience by improving the quality of the entire process. The reproduction of standardized norms and models serves in turn to protect against accidents, thus reproducing those catastrophic situations that the worker must know how to handle even if in fact they occur with very limited statistical probability[22–25]. Simulations allow for very useful reflection on the results of decisions and any mistakes that may be made. Also, simulation reduces the occupation of machines and equipment that are often already overloaded by normal work operations. In healthcare, one of the most recent steps is the introduction of simulation-based medical teaching and learning[26,27]. Simulation-based medical education is defined as any educational activity that uses simulation tools to reproduce clinical scenarios, particularly in acute care[2,16,27]. In simulation-based education, learners engage with individuals, simulators, computers, or task trainers to achieve specific learning objectives. The extent to which a simulation mirrors real-life scenarios is referred to as fidelity. High-fidelity simulation involves highly realistic environments and scenarios, offering an elevated level of interactivity and immersion to enhance learner engagement and skill acquisition[28].Medical simulation induces the acquisition of clinical skills through deliberate practice rather than through the learner's learning style. Simulation tools act as an alternative to real patients and in this way, mistakes can be made without fear of harming the patient. It is also cost-effective when used correctly[29]. Simulation can be effectively integrated into existing curricular frameworks, offering a realistic and immersive learning environment. High-fidelity simulators, capable of speaking, breathing, blinking, and exhibiting physical responses, enhance emotional engagement and facilitate experiential learning. These simulations can be tailored to meet the educational needs of various medical specialties, including anesthesiology, emergency and trauma medicine, intensive care, obstetrics, pediatrics, and radiology. Additionally, simulation-based training supports the skill development of a wide range of healthcare professionals, such as nurses, paramedics, and respiratory therapists[30,31]. Simulation can be applied in primary health care settings to enhance life-saving manoeuvres, clinical competencies, communication skills, and the overall quality of care for patients with chronic conditions[32]. However, a major challenge in the field of medical simulation remains the methodological weakness of existing evidence. Much of the available literature is descriptive and lacks generalizability. Only a limited number of studies have demonstrated a direct and measurable impact of simulation-based training on clinical outcomes[33].

Methods

Hyperbaric chamber simulation

The simulation described here involves a system consisting of two chambers: a main chamber and an airlock, and three doors, one outside the airlock, one outside the main chamber and one between the two chambers. The main chamber is fitted with 12 oxygen and/or medical gas masks (Fig. 1). Each chamber is equipped with a safety valve that releases pressure to the outside to prevent it from exceeding preset threshold values. A one-way valve between the main chamber and the airlocks ensures that the pressure within the airlock does not exceed the pressure of the main chamber. The flow of oxygen and/or medical air into and out of both chambers can be regulated via suitable valves controlled from the central control panel. The system also includes a monitor

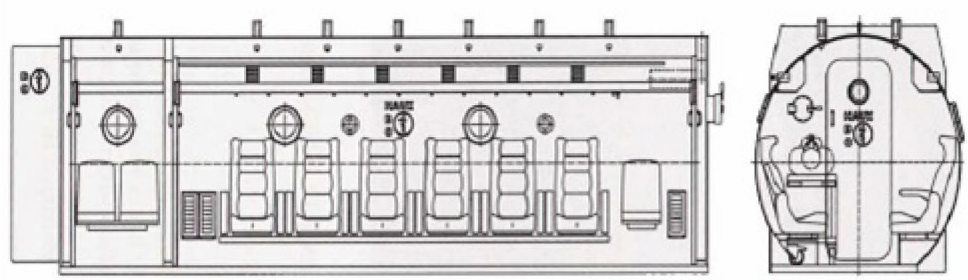

Fig. 1. Main chamber representation.

that allows operators to check the internal conditions of the chambers and display alarm situations, such as fire or physical disturbances to the inhabitants. A dedicated button triggers the fire-fighting system, which forcibly injects water into the selected chamber. Other buttons are used to control the lighting within each chamber. The air supply for both chambers comes from a silo, which is replenished by a special compressor after the air has undergone adequate filtration. Medical air and oxygen are stored in two separate cylinder sets, and their supply can be adjusted during simulation. The water for the fire-fighting system is stored in a tank, which is kept under pressure by air from a special cylinder system. Both the cylinder pressure and water level can be set during the simulation. Figure 2 illustrates the overall functional structure of the simulated hyperbaric system, including the operation of valves, measurements provided by instruments, lighting controls, and the opening and closing of doors.

Simulator development

The proposed simulator was developed using Java within the NetBeans 8 integrated development environment. The simulator employs a MySQL database as a backend for data storage and retrieval. Model development was predicated upon a comprehensive analysis of hyperbaric chamber operational principles, incorporating relevant physical and biological processes. NetBeans 8 facilitated modular software design and seamless integration of external libraries. A graphical user interface (GUI) was implemented using the Swing framework, enabling users to define critical parameters such as pressure and session duration, and to visualize simulated physiological responses. Data persistence and efficient database interactions were achieved through the integration of the MySQL Connector/J driver, with the JAR file incorporated into the NetBeans project.

Simulation software

The hyperbaric chamber simulator is built on software developed in JAVA, featuring two main panels:

- Back end: manages administration tasks and controls the simulation results.

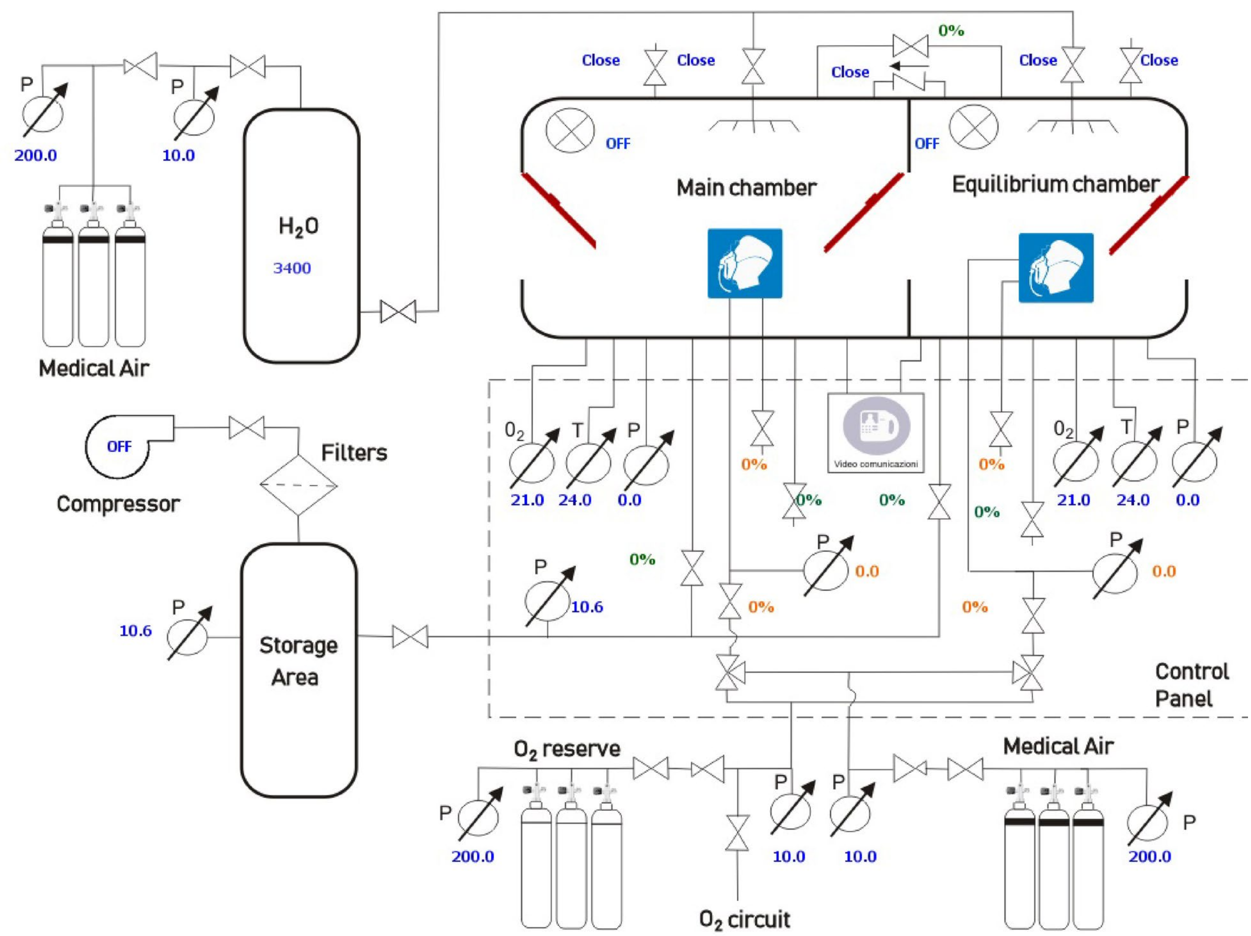

Fig. 2. The overall functional structure of the simulated hyperbaric chamber system, including the main chamber and airlock. It shows the arrangement and interaction of various components such as valves, pressure and temperature sensors, oxygen and medical air supply systems, fire-fighting mechanisms, and control interfaces. The figure highlights the pathways for air and gas flow, the locations of safety and emergency valves, and the control points for managing the chamber environment.

- Front end: provides the user interface for interacting with the simulation.

The software is hosted on a web server and accessed through the JNLP (Java Network Launch Protocol). All relevant data for administration and simulation are stored in a MySQL database on the same server.

Simulation panel (front end)
The simulation panel, or front end of the application, serves as the user interface. It includes controls, status indicators, and measuring instruments (Fig. 3). The interface is organized into the following main areas:

- Main chamber.
- Equilibrium chambers.
- Communications and control.
- Simulation management.

Main chamber
This area of the simulation panel provides tools and commands for managing the main chamber. It allows the simulation of air control (inflow and outflow), mask management, door operations, internal lighting, and the measurement of various parameters such as pressure, temperature, humidity, and oxygen levels. Additional controls include the activation of the fire extinguishing system, management of gases supplied to the masks, and the thermal air conditioning system. These controls and instruments become active only after the simulation procedure starts.

As shown in Fig. 4, the main chamber includes the following controls and instruments:

- Air inlet valve: Controlled by a slider to regulate the inflow of compressed air into the main chamber. Air outlet valve: Controlled by a slider to regulate the outflow of compressed air from the main chamber.
- Door management: A button opens or closes the main chamber door with an indicator light displaying the door's status. The door cannot be opened unless the pressure between the chamber and the outside is equalized. Attempts to open the door without pressure equilibrium trigger both a sound and a log warning. Light management: A button toggles the main room light on or off.

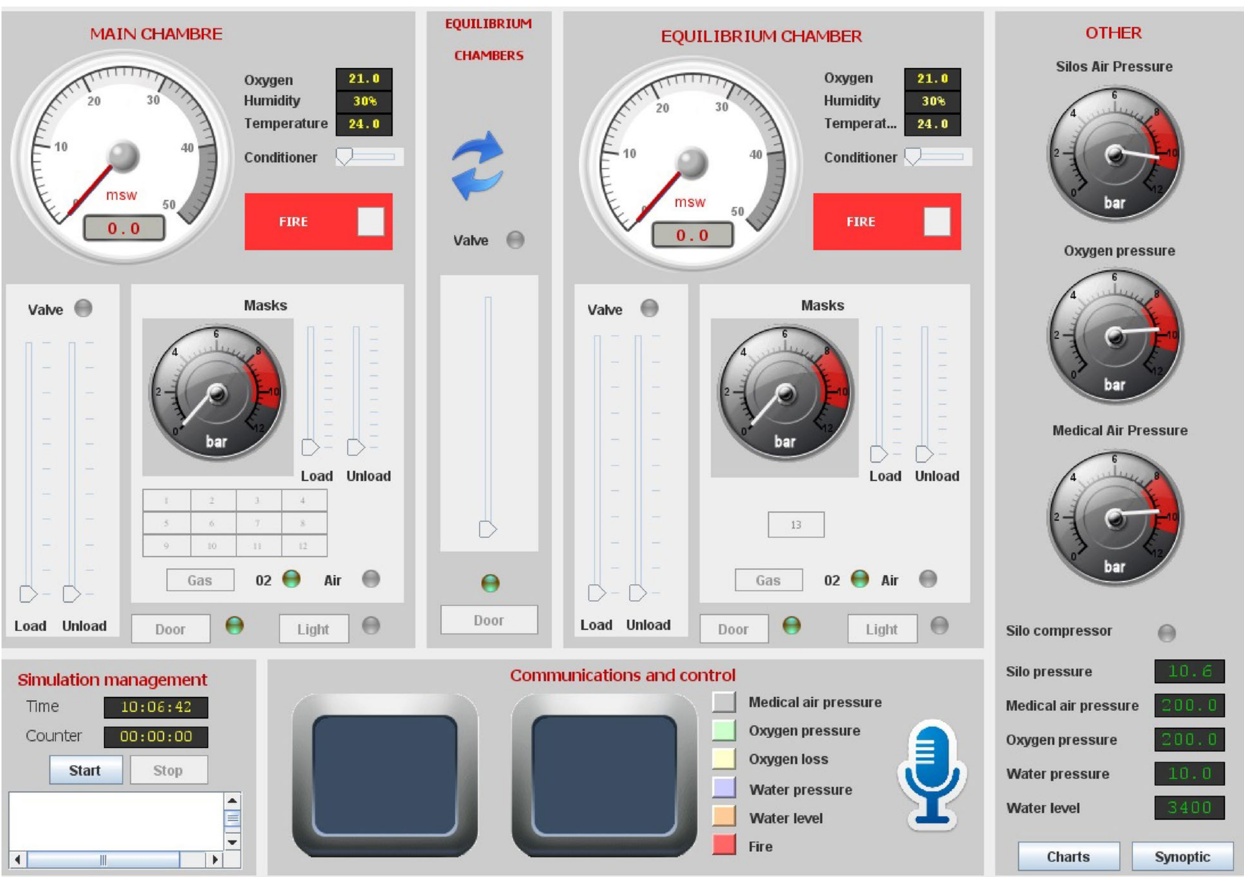

Fig. 3. Hyperbaric chamber simulator front end. The interface is divided into sections for managing the main chamber, equilibrium chambers, communications and control, and simulation management. It includes various controls, status indicators, and measuring instruments that allow users to simulate and monitor different aspects of the hyperbaric chamber environment, such as air and gas flow, lighting, and emergency procedures.

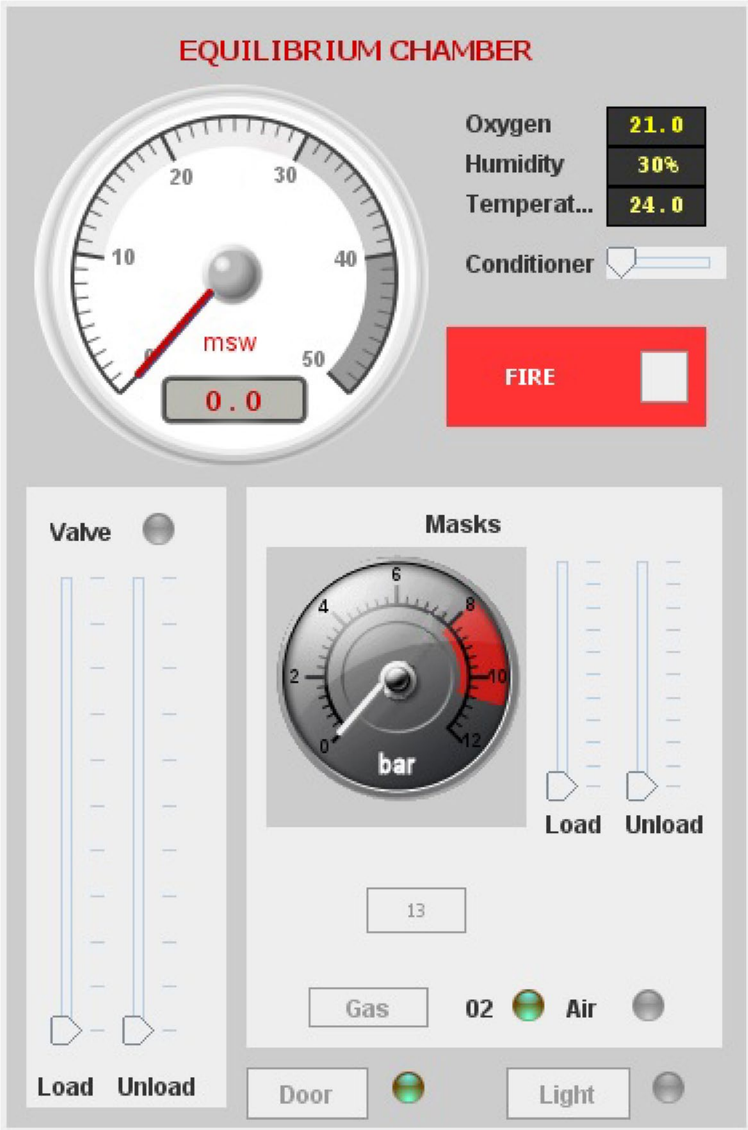

Fig. 4. Main chamber control panel.

- Internal pressure manometer: Measures the pressure inside the main chamber, displaying both analogue and digital readings.
- Oxygen percentage measurement: A digital instrument measuring the oxygen percentage inside the chamber, useful for detecting oxygen leaks from masks.
- Humidity measurement: A digital instrument measuring humidity inside the main chamber.
- Temperature measurement: A digital instrument measuring the temperature inside the main chamber, crucial during pressure changes.
- Oxygen/air mask activation commands: An analogue instrument measuring pressure in the mask circuit.
- Oxygen/air inlet valve: Controlled by a slider to regulate the flow of medical air/oxygen into the mask circuit.
- Oxygen/air outlet valve: Controlled by a slider to regulate the flow of medical air/oxygen out of the mask circuit.
- Emergency valve: An indicator showing when the emergency valve opens, triggered if the main chamber pressure exceeds the safety threshold set in the general configuration panel.

Equilibrium chamber

This area of the panel provides tools and commands for managing the equilibrium chamber. It allows for the simulation of air control (incoming and outgoing), mask management, door operations, internal lighting, parameter measurements, activation of the fire extinguishing procedure, control of gases supplied to the masks, and regulation of the thermal air conditioning system. These controls and instruments are activated only after the simulation procedure begins.

As shown in Fig. 5, the equilibrium chamber includes the following controls and instruments:

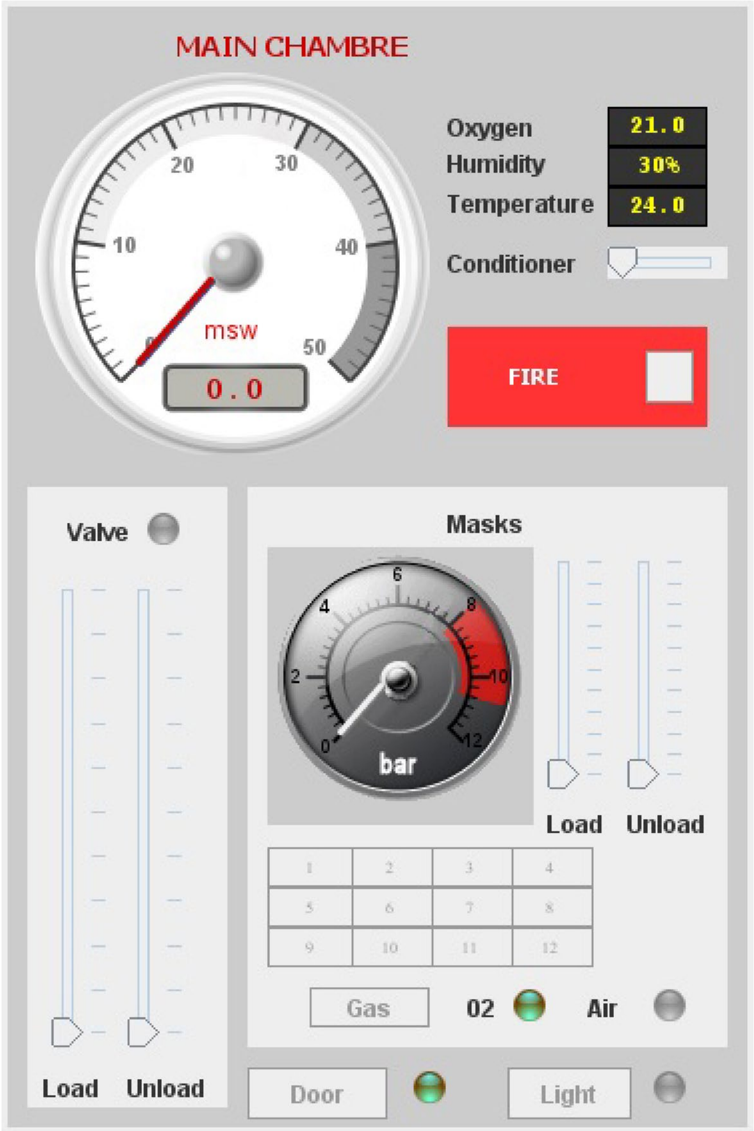

Fig. 5. Equilibrium chamber control panel.

- Air inlet valve: Controlled by a slider to regulate the inflow of compressed air into the airlock.
- Air outlet valve: Controlled by a slider to regulate the outflow of compressed air from the airlock.
- Door management: A button opens or closes the airlock door, with an indicator light showing the door status. The door will not open unless the pressure between the airlock and the outside is equalized. Attempts to open the door without pressure equilibrium trigger a sound and a log warning.
- Light management: A button toggles the airlock light on or off, with an indicator light showing the lighting status.
- Internal pressure manometer: Measures the pressure inside the airlock, displaying both analogue and digital readings, with units in msw (meters of seawater).Oxygen percentage measurement: A digital instrument measuring the oxygen percentage inside the equilibrium chamber.
- Humidity measurement: A digital instrument measuring the humidity inside the equilibrium chamber.
- Temperature measurement: A digital instrument measuring the temperature inside the equilibrium chamber, essential during pressure changes.
- Oxygen/air mask activation controls: A button to activate or deactivate the use of the mask.
- Gas type selection: A button to select the gas (oxygen or medical air) supplied to the masks.
- Oxygen/air pressure manometer: An analogue instrument measuring pressure in the mask circuit.
- Oxygen/air inlet valve: Controlled by a slider to regulate the flow of medical air/oxygen into the mask circuit.
- Oxygen/air outlet valve: Controlled by a slider to regulate the flow of medical air/oxygen from the mask circuit.
- Emergency valve: An indicator showing the emergency valve opens, triggered if the pressure in the equilibrium chamber exceeds the safety threshold set in the general configuration panel.

Equilibrium chambers

This area of the panel controls the interaction between the equilibrium chamber and the main chamber (see Fig. 3). From here, you can manage the valve that brings the two chambers into pressure equilibrium, an essential condition before the door between the chambers can be operated. Additionally, there is also a one-way valve that activates when the pressure in the airlock exceeds the pressure in the main chamber. The door button allows for opening or closing the door between the two chambers. A red indicator shows when the door is closed, while a green indicator shows the door open. It is important to consider that the opening of the door is conditional on the equilibrium of pressure between the two chambers, so the door will not open if this condition is not fulfilled; a sound and a warning in the log indicate attempts to open the door if there is no equilibrium between the two chambers.

Simulation management

This area of the control panel allows you to start and stop the simulation. At the bottom, there is a text entry field where you can add notes, which will be stored along with the simulation data. The area also displays the current time and a counter showing the elapsed time since the simulation began. When you activate the simulation using the Start button, a window will appear with options to select from various simulation settings. This feature lets you choose between a standard simulation, where the user follows a specific operating procedure, or a simulation with potential anomalies that require management.

Specifically, the available conditions are:

- Normal simulation: A standard simulation controlled entirely by the user, without any faults.
- Fire 1: A simulation where a fire occurs at a random time within a 5-minute interval from the start.
- Fire 2: A simulation where a fire occurs at a random time within a 5-minute interval from the start, with random initial conditions regarding the water level and pressure of the fire extinguishing system.
- Gas anomalies 1: A simulation involving an oxygen leak from the masks.
- Gas anomalies 2: A simulation with random initial conditions regarding the pressure of the tanks containing oxygen and medical air.

Communication and control

This area of the control panel includes two monitors that display the status of various conditions inside each room. These conditions include:

- Light status: Indicates whether the light is on or off.
- Fire detection: Alerts if a fire is detected within the room.
- Occupant disturbance: Monitors and displays any physical disturbances involving the occupants.

These features ensure that the simulation environment is closely monitored and managed, providing a realistic and safe training experience.

General purpose tools

As shown in Fig. 6, this area of the control panel features both analogue and digital instruments for monitoring various general-purpose parameters. Specifically, there are three analogue instruments that display the following:

- Silo air pressure: Monitors the pressure used for loading the two chambers.
- Oxygen pressure: Measured after the reduction valve.
- Medical air pressure: Measured after the reduction valve.

An indicator light signals the start of operation of the compressor, which recharges the silos with air for loading the two chambers. There are five digital instruments that display the following:

- Silo air pressure: Used for loading the main chamber and the airlock.
- Oxygen pressure: Measured before the reduction valve, at the tank outlet.
- Medical air pressure: Measured before the reduction valve, at the tank outlet.
- Water pressure: Used by the fire-fighting system.
- Water level: Used by the fire-fighting system.

The values displayed by the digital instrumentation can be adjusted to simulate intervention operations by clicking on the corresponding item. For example, if the water level in the fire-fighting system is insufficient, the user clicks on the Water Level item. A window will open, allowing the user to enter the desired water level; the filling of the water tank will then be simulated. In some simulation modes, the software may propose inadequate values, and it will be up to the user to correct them. For instance, an insufficient water level will prevent effective fire management if a fire occurs during the simulation.

At the bottom of this panel, there are two additional buttons:

- Graphs: Opens the graphical display of the trends of certain parameters.
- Synoptic: Opens the synoptic display of the simulated system.

Fig. 6. The general-purpose tool panel available on the control interface of the hyperbaric chamber simulator.

Synoptic visualisation of the simulation
As shown in Fig. 2, the synoptic panel can be activated from the simulation interface. It provides a schematic view of the system, displaying all the involved variables. This panel allows for comprehensive monitoring of the following:

- ON/OFF valve status : main chamber emergency valve, airlock emergency valve, main chamber fire water valve, airlock fire water valve, one-way airlock valve between main chamber and airlock;

- proportional valve status of : main chamber loading valve, airlock unloading valve, main chamber jig loading valve, airlock unloading valve;
- functional status: main chamber lighting, airlock lighting, compressor operation for air storage for main chamber and airlock;
- door opening status: main chamber, airlock, passage between main chamber and airlock;
- measuring instruments: pressure, oxygen and temperature of the main chamber, pressure, oxygen and temperature of the airlock, oxygen pressure for masks before and after the reduction valve, medical air pressure for masks before and after the reduction valve, water pressure of the fire-fighting circuit before and after the reduction valve, water level of the fire-fighting circuit.

This synoptic panel ensures that all critical parameters and statuses are easily accessible and monitored in real-time, enhancing the effectiveness and safety of the simulation.

Graphical visualisation of the simulation

A window, accessible from the simulation interface, provides a graphical representation of certain simulation variables. These include:

- Pressure, temperature, and oxygen levels in the main chamber.
- Pressure, temperature, and oxygen levels in the airlock.

As shown in Fig. 7, next to the graphical representation, you can also view a list of actions performed by the user and any events that have occurred. This feature allows for a comprehensive overview of the simulation's progress, helping to analyze the impact of various actions and events in real-time.

Simulated breakdowns

The software performs regular checks on the variables in play as it can randomly present unsafe initial values for the performance of a procedure. The variables to be monitored include silo pressure, medical air pressure, oxygen pressure, fire-fighting water pressure, fire-fighting water level. When the simulation is started using the Start button in the Simulation Management panel, a window appears allowing the user to choose from several simulation settings. The available conditions are:

- *Normal simulation*, a standard simulation, fully controlled by the user, without any faults;
- *Fire 1*, a simulation where a fire is pre-selected, occurring at a random time within a 5-minute interval from the start of the simulation;
- *Fire 2*, a simulation where a fire occurs at a random time within an interval of 5 min from the start of the simulation with a random starting condition regarding the water level and pressure of the fire extinguishing system;
- *Gas anomalies 1*, a simulation involving an oxygen leak from the masks;
- *Gas anomalies 2*, a simulation of a random starting condition regarding the pressure of the tanks containing oxygen and medical air.

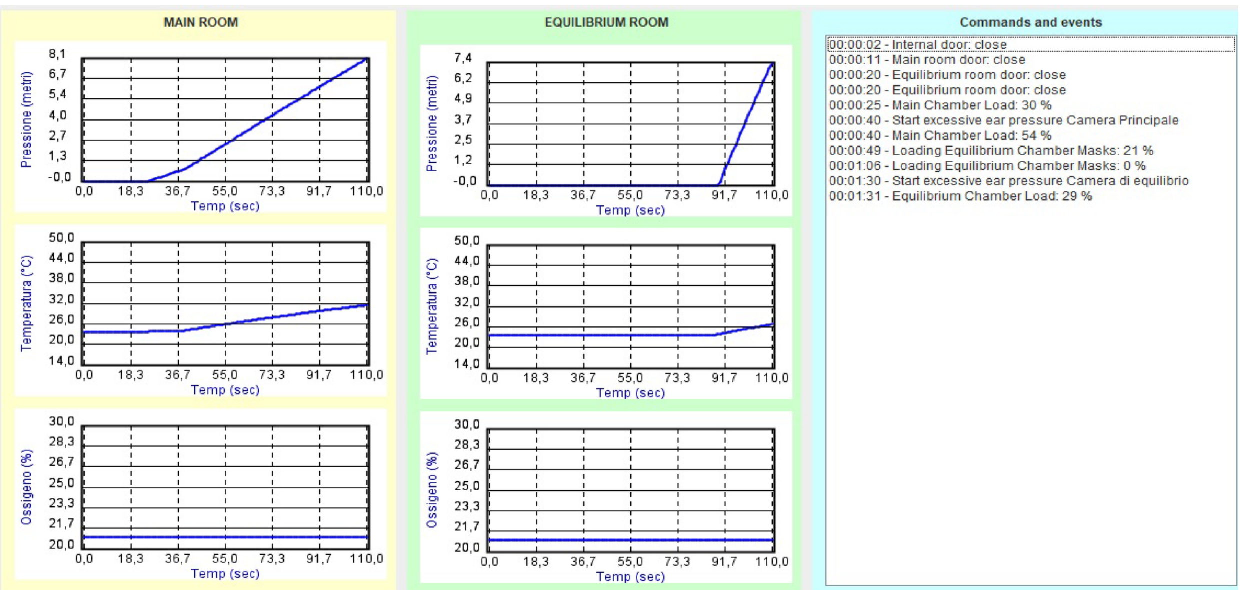

Fig. 7. Graphical visualisation of the simulation.

During the regular simulation, failures may occur randomly, such as fire and loss of oxygen. The require specific actions: the fire necessitates manual activation of fire-fighting procedures, while oxygen loss prompts the user to correctly place the mask and initiate a chamber flushing procedure.

Administrative panel (back-end)

The administration panel provides the tools necessary to manage the credentials of users authorised to access the simulator. It also allows for displaying the activities performed by each user in both graphical and tabular format. Additionally, in the Technical Specifications section, users can define the dimensional and functional parameters of the hyperbaric chamber.

Simulated breakdowns

The administrative panel provides the tools needed to manage the credentials of users authorised to access the simulator and to display the activity in both graphical and tabular formats. In the Technical Characteristics section, it is also possible to define the dimensional and functional parameters of the hyperbaric chamber.

User management

This section of the control panel provides all the necessary tools for user administration, including creating, editing, and deleting a user. For each user, the following information is stored: first name, last name, username, password and email. This panel also allows you to view the list of simulations conducted by each user. By selecting a user and a simulation, you can access graphs and command logs in the relevant sections, as shown in Fig. 8.

Graphic report

This section (Fig. 9) shows graphs of the simulation performed for each chamber, displaying pressure (in meters depth), temperature (°C), and oxygen percentage (%). The data corresponds to the user and simulation selected in the Users section.

Command logs and warnings

This section of the panel allows you to view a chronological sequence of operations performed by the user using the simulator, such as opening/closing doors, operating both regular and emergency valves, activating special conditions, etc. It also displays any warnings generated during the simulation, including the opening of emergency valves, fire events, and rapid pressure increases (see Fig. 10).

Technical specifications

This section of the panel allows you to define various parameters useful for simulation (Fig. 11). These parameters are grouped into the following categories:

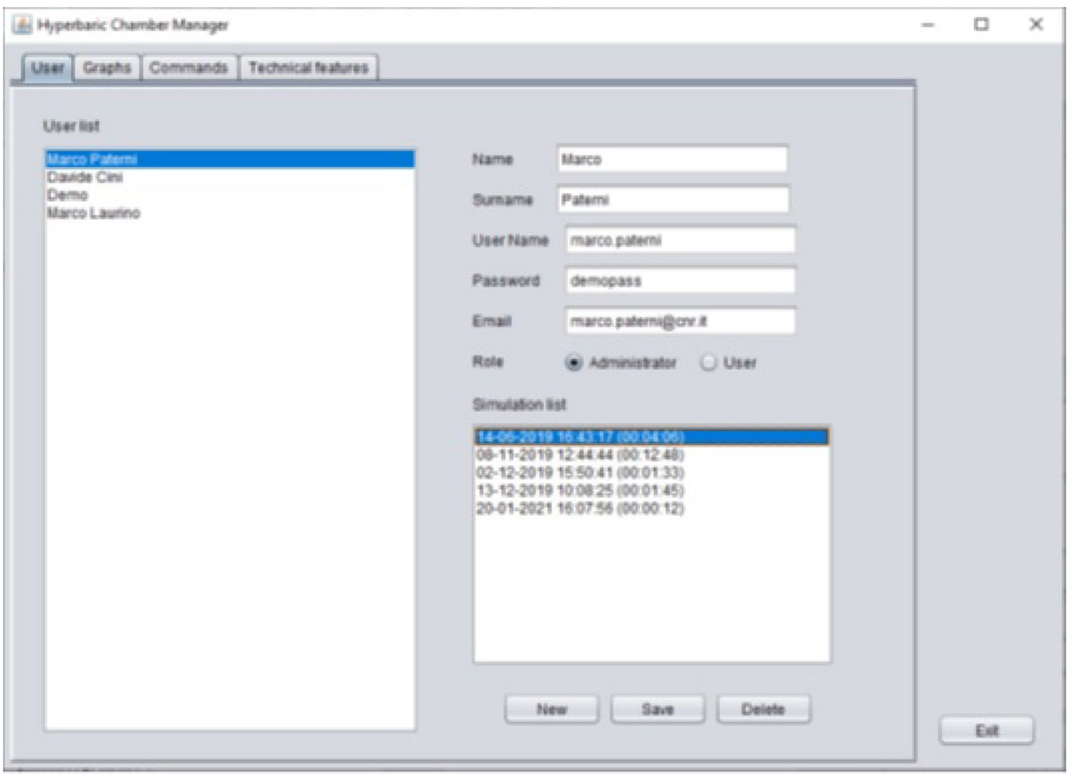

Fig. 8. Control panel interface.

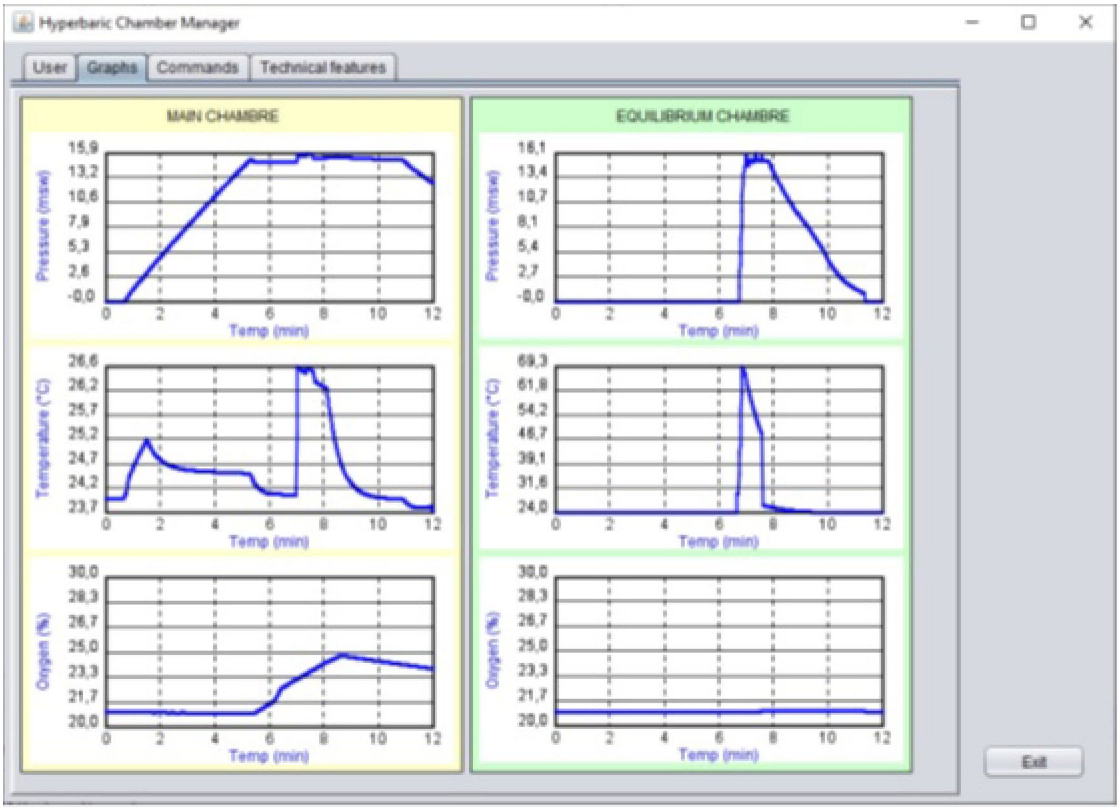

Fig. 9. Simulation interface.

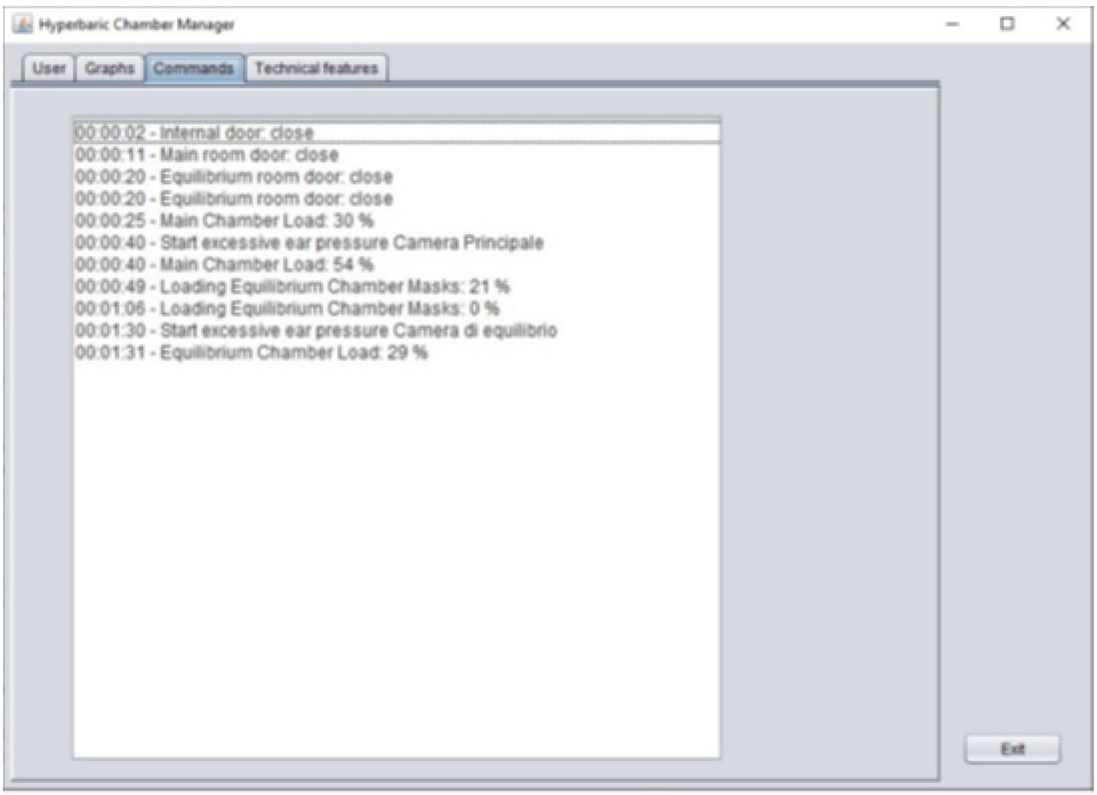

Fig. 10. Command logs and warnings interface.

Fig. 11. Parameters set up interface.

- Main chamber: parameters describing the geometric and functional characteristics of the main chamber, including length, radius, thickness, maximum opening of the loading and unloading valves, oxygen levels, minimum and maximum thresholds for activating the safety valve, and maximum openings for the mask loading and unloading valves.
- Equilibrium chamber: parameters describing the geometric and functional characteristics of the equilibrium chamber, including length, radius, thickness, maximum opening of the loading and unloading valves, oxygen levels, minimum and maximum thresholds for activating the safety valve, and maximum openings for the mask loading and unloading valves.
- General parameters: parameters describing the environmental and functional aspects of the entire hyperbaric chamber system, including environmental temperature, silo volume and pressure for oxygen, silo volume and pressure for medical air, fire water volume, and fire prevention water pressure.

Simulation results

Several simulation scenarios are described below to demonstrate how the simulator is used.

1. Generic simulation example: descent to 18 m in 5 min with oxygen;
2. stay at 18 m for 5 min with oxygen (during this phase, an external operator is required to enter the main chamber through the airlock);
3. ascent to 12 m in 6 min with medical air;
4. permanence to 12 m for 5 min with oxygen;
5. ascent to 6 m in 4 min with medical air;
6. 6 m for 5 min with oxygen;
7. ascent to 0 m in 7 min with medical air.

The graphs shown in Fig. 12 highlight the various stages of the descent and the initial rise in temperature. The oxygen levels remain stable, indicating that the masks have not leaked. Additionally, the rapid descent of the operator, who entered the airlock to reach the main chamber is evident.

The LOG displays the operations carried out during the procedure described above, along with any events, as shown in Fig. 13.

Simulation with failure (fire)

In the scenario, a fire outbreak is simulated, highlighting the consequences of poor operator response. The simulation follows these steps (Fig. 14):

1. the operator initiates a rapid descent to 18 m in 2.4 min with oxygen and does not check the situation of the system;

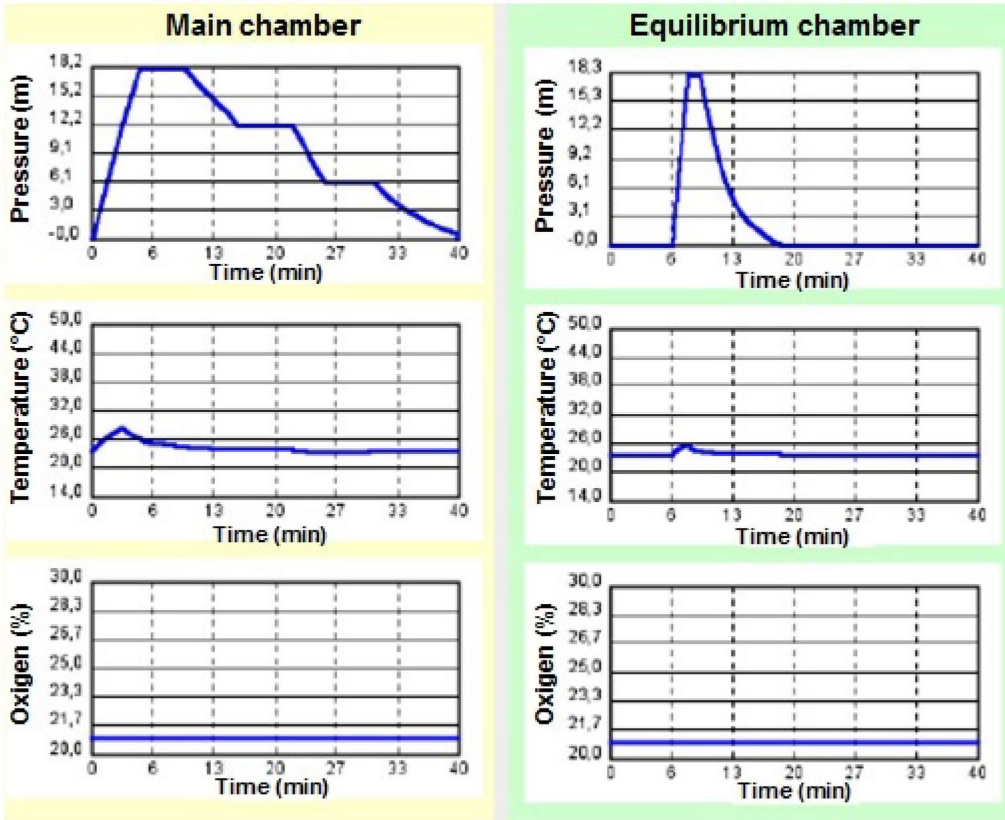

Fig. 12. Generic simulation.

2. during the descent, the air conditioning system is activated to regulate the temperature increase;
3. a fire breaks out in the main chamber;
4. the operator activates the sprinkler system after 24 s;
5. after 20 s, the fire-fighting system runs out of water without the fire itself having been extinguished;
6. the operator starts draining the main chamber;
7. the operator switches the mask supply to medical air.

The LOG highlights the ignition of the fire and the operator's mismanagement, leading to an inability to extinguish the fire and evacuate the room in time. The following critical errors are recorded:

- Failure to check system readiness: The operator did not verify the water level and pressure of the fire-fighting system, resulting in an inadequate response when the fire occurred.
- Delayed response: The operator took 20 s to activate the fire-fighting system, wasting valuable time.
- Improper mask management: The operator failed to switch the mask gas to medical air immediately.
- Delayed emergency actions: The operator hesitated to initiate the rapid discharge of the main chamber.

The combined effect of these errors would have resulted in lethal consequences for the occupants of the hyperbaric chamber. This simulation demonstrates the importance of proper training in handling critical situations, allowing operators to learn and improve without real-world risks.

Hyperbaric therapy table simulation
In this scenario, we simulate hyperbaric therapy table No. 5 of the US navy, which is one of the most widely used protocols for clinical hyperbaric treatment. This protocol is typically used in cases of such as no decompression emergencies, for example, during emergency ascents.

The procedure in this simulation follows these steps:

1. rapid descent to 18 m in 2.4 min with oxygen;
2. stay at 18 m for 20 min with oxygen;
3. stay at 18 m for 5 min with medical air;
4. ascent to 9 m in 30 min with oxygen;
5. stay at 9 m for 5 min with medical air;
6. stay at 9 m for 20 min with oxygen;
7. stay at 9 m for 5 min with medical air;

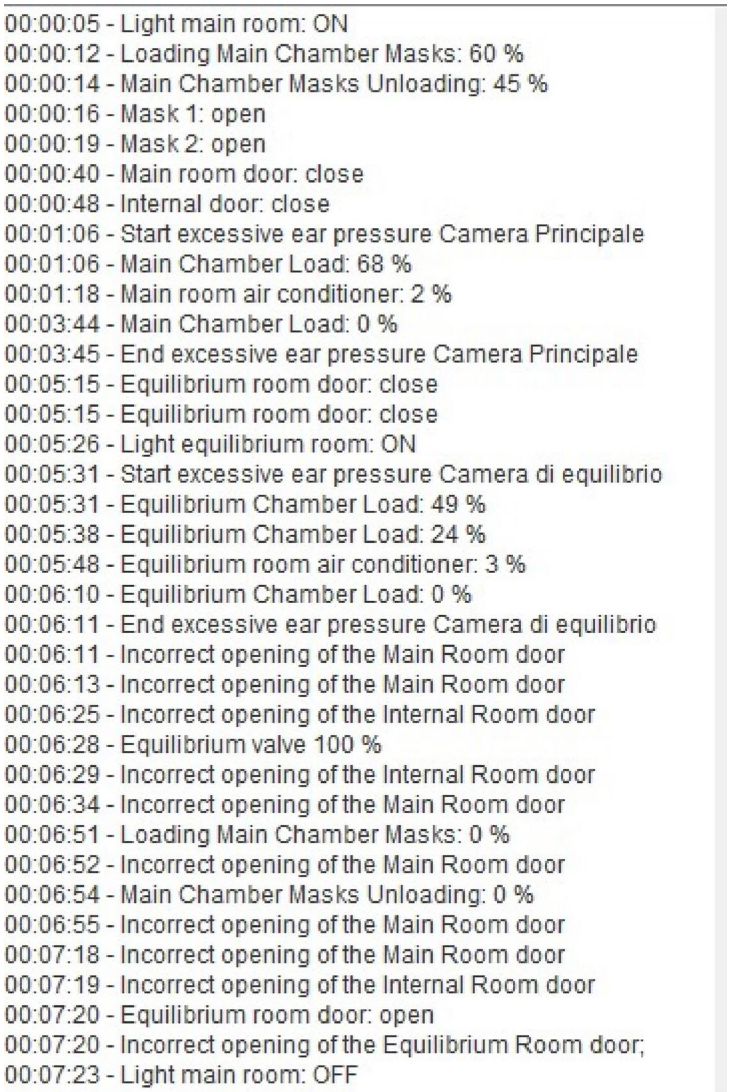
00:00:05 - Light main room: ON
00:00:12 - Loading Main Chamber Masks: 60 %
00:00:14 - Main Chamber Masks Unloading: 45 %
00:00:16 - Mask 1: open
00:00:19 - Mask 2: open
00:00:40 - Main room door: close
00:00:48 - Internal door: close
00:01:06 - Start excessive ear pressure Camera Principale
00:01:06 - Main Chamber Load: 68 %
00:01:18 - Main room air conditioner: 2 %
00:03:44 - Main Chamber Load: 0 %
00:03:45 - End excessive ear pressure Camera Principale
00:05:15 - Equilibrium room door: close
00:05:15 - Equilibrium room door: close
00:05:26 - Light equilibrium room: ON
00:05:31 - Start excessive ear pressure Camera di equilibrio
00:05:31 - Equilibrium Chamber Load: 49 %
00:05:38 - Equilibrium Chamber Load: 24 %
00:05:48 - Equilibrium room air conditioner: 3 %
00:06:10 - Equilibrium Chamber Load: 0 %
00:06:11 - End excessive ear pressure Camera di equilibrio
00:06:11 - Incorrect opening of the Main Room door
00:06:13 - Incorrect opening of the Main Room door
00:06:25 - Incorrect opening of the Internal Room door
00:06:28 - Equilibrium valve 100 %
00:06:29 - Incorrect opening of the Internal Room door
00:06:34 - Incorrect opening of the Main Room door
00:06:51 - Loading Main Chamber Masks: 0 %
00:06:52 - Incorrect opening of the Main Room door
00:06:54 - Main Chamber Masks Unloading: 0 %
00:06:55 - Incorrect opening of the Main Room door
00:07:18 - Incorrect opening of the Main Room door
00:07:19 - Incorrect opening of the Internal Room door
00:07:20 - Equilibrium room door: open
00:07:20 - Incorrect opening of the Equilibrium Room door;
00:07:23 - Light main room: OFF

Fig. 13. Commands and events.

8. ascent to 0 m in 30 min with oxygen.

The simulation graphs (Fig. 15) highlight the different stages of the procedure, including:

- The descent phase and the initial rise in temperature, which is compensated by the activation of the air conditioning system.
- The oxygen levels remain stable throughout the simulation, demonstrating that there are no leaks in the masks.

Pilot study

To evaluate the effectiveness of using the proposed simulator in the training process, we performed a pilot study by collecting data from 27 participants recruited from the "Advanced Training Course for Hyperbaric Technicians" and the "2nd level Master Degree in Underwater and Hyperbaric Medicine - Piergiorgio Data" of Scuola Superiore Sant'Anna of Pisa in collaboration with Institute of Clinical Physiology of the CNR of Pisa. This study protocol was carried out in accordance with Good Clinical Practice and the Declaration of Helsinki statements concerning medical research in Humans. The local Ethical Committee of Scuola Superiore Sant'Anna, approved this study protocol (study registration number 40/2024). Informed consent was obtained from all subjects involved in the study.

A measure of effectiveness was evaluated by the students prior to entering the real hyperbaric chamber. Free access to the simulation software was provided and the students were able to use it to test their skills. The recording system monitored all activities conducted to analyse:

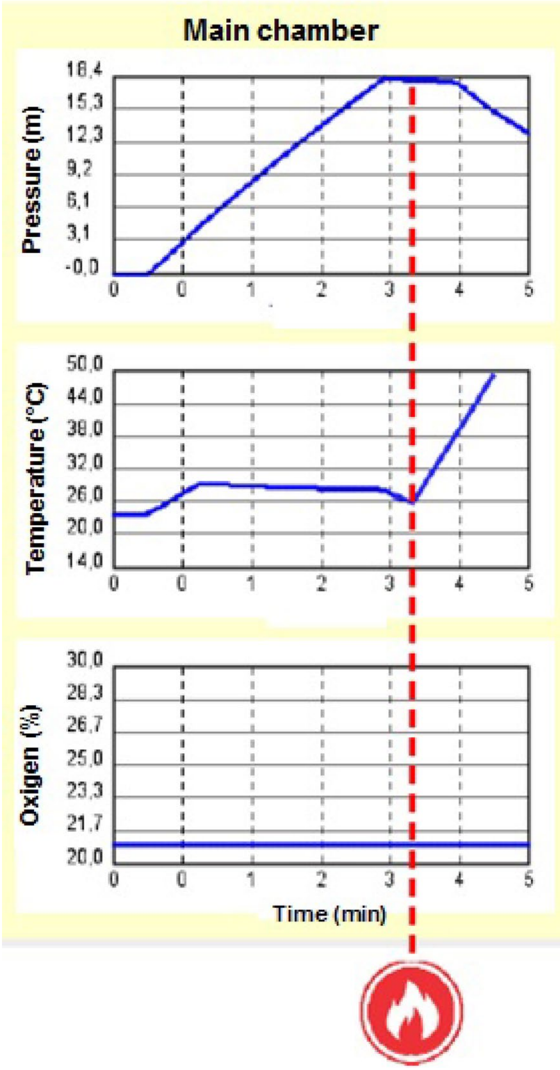

Fig. 14. Simulation with failure.

- Manoeuvre errors, i.e. incorrect manoeuvres conducted regarding the use of valves, mechanical systems, initial checks (checklists), response to faults, etc.
- Functional errors, i.e. the deviation of pressure values during descent and ascent relative to the reference tables.

These data were useful for assessing the students' learning curve. In the context of manoeuvre errors, the frequency was assessed as illustrated in Fig. 16. There is a significant prevalence of the failure to carry out the initial checklist, followed by delays in activating the fire-fighting procedure and the failure to detect oxygen leaks from masks. Other errors such as attempting to open the door with the pressurised chamber, exceeding the maximum pressure, incorrect flushing, excessive pressure variation and temperature control also occur, although to a lesser extent. It is interesting to observe how these errors decrease very quickly in the various attempts to use the simulator. The simulation of tragic events such as the unsuccessful attempt to extinguish a fire because of the incorrect execution of the initial checklist and thus in the absence of the necessary air pressure and/or water quantity of the fire-fighting system has a great influence. Figure 17 shows the mean value of the errors and their standard deviation. As depicted in the figure, the mean value of manoeuvre errors drops below the unit value after the fifth simulator attempt. Figure 18 shows the functional errors over time. Unlike manoeuvring errors, students need more time to reduce this type of error significantly. This highlights a greater difficulty in acquiring the skills necessary to comply with the descent and ascent tables. The average error drops below 5% after the seventh attempt.

In Table 1 was reported the analysis to evaluate whether there is a statistically significant difference between the values recorded at the initial time (untrained students) and those at the final time (students trained with the simulator). Since the data derive from measurements performed on the same subjects at two different times, a t-test for paired samples was applied. Furthermore, to quantify the magnitude of the observed effect, Cohen's d was calculated.

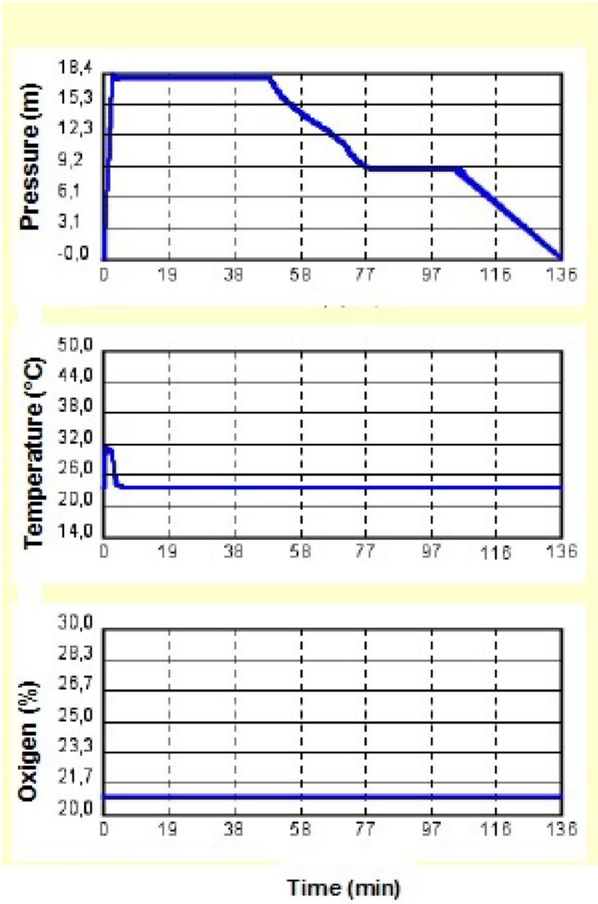

Fig. 15. Simulation.

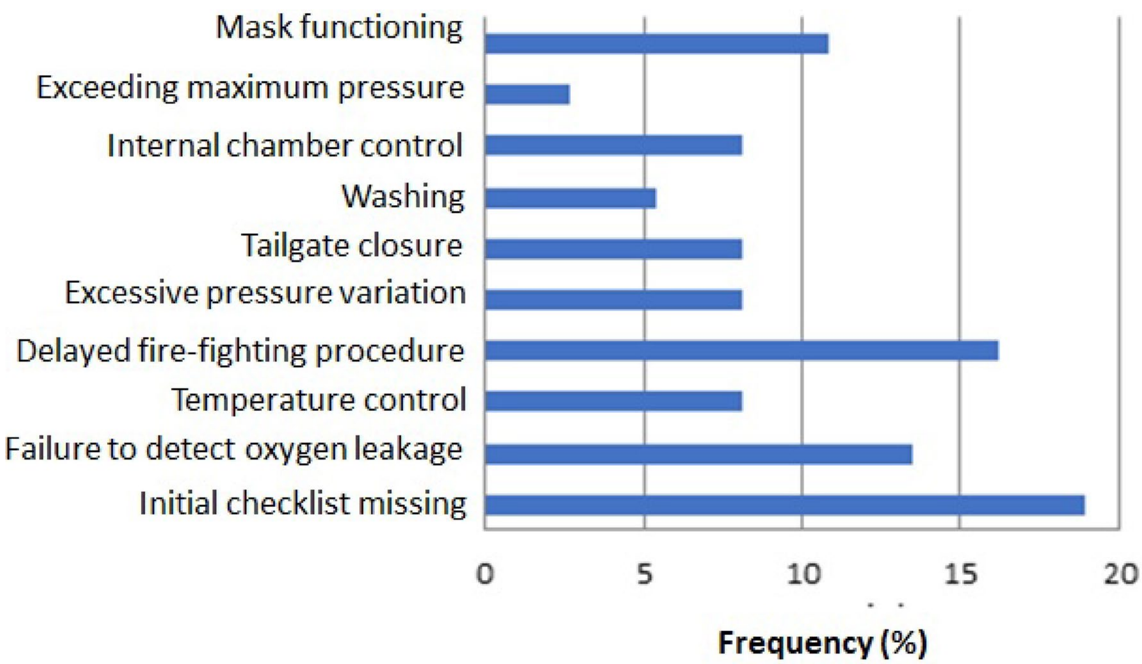

Fig. 16. Manoeuvre errors in the pilot study.

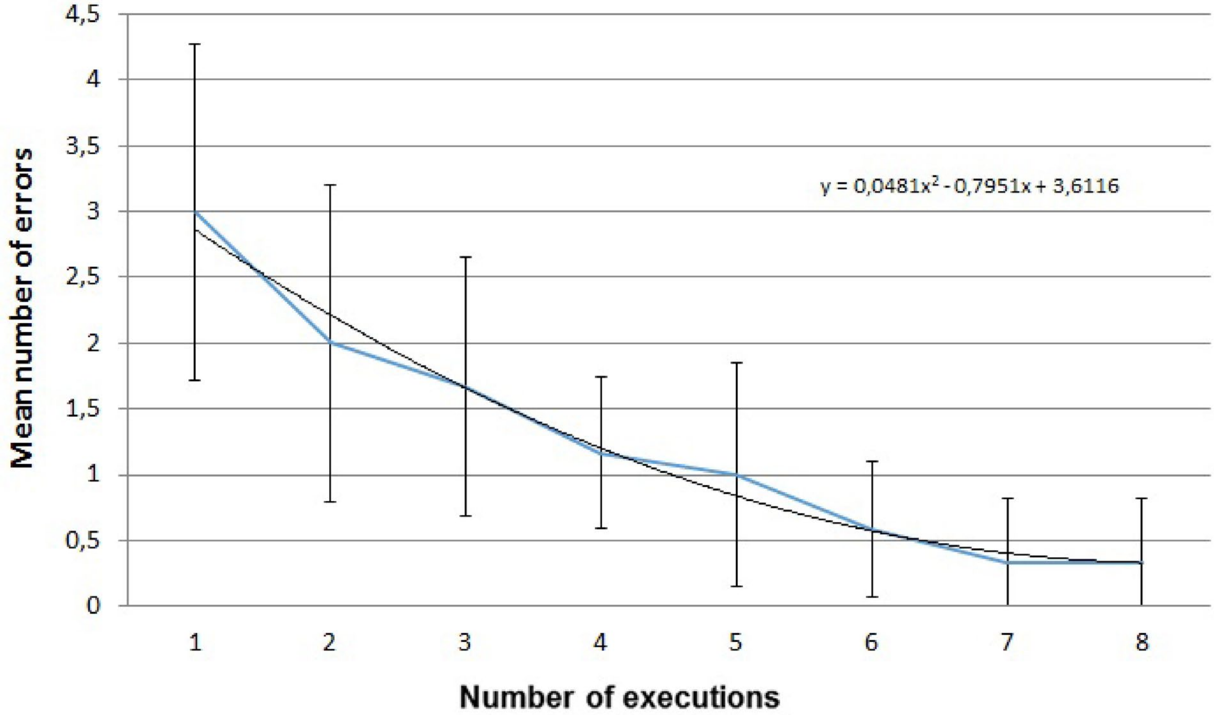

Fig. 17. Mean value of the errors in the pilot study.

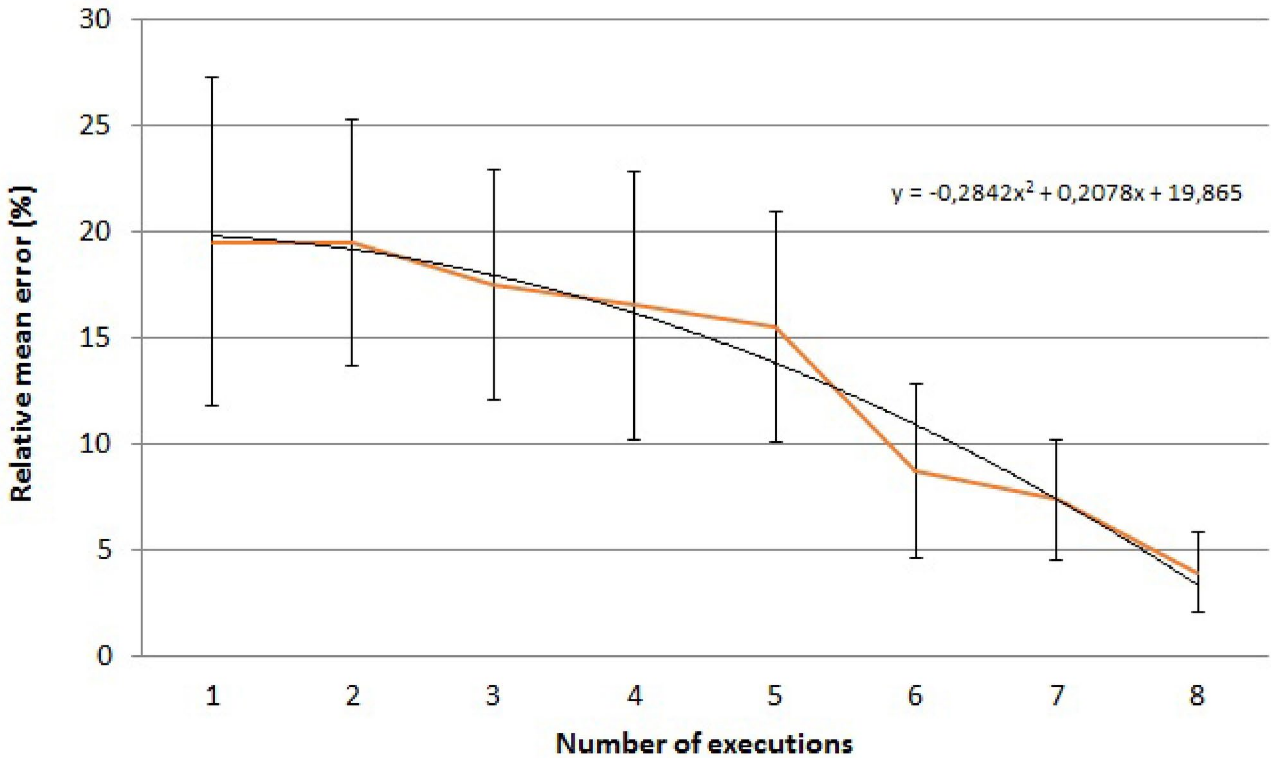

Fig. 18. Functional errors over time in the pilot study.

Element of comparison	Errors (mean ± sd)		T-test	Cohen d coefficient
	Start of training	Start of training		
Maneuvering errors	3.25 ± 1.29	1.25 ± 0.62	t = 7.34, $p < 0.05$	d = 2.12
Functional errors	19.5 ± 7.73	3.92 ± 1.88	t = 8.17, $p < 0.05$	d = 2.36

Table 1. Comparison between values recorded at the initial time and at the final time. *sd* standard deviation.

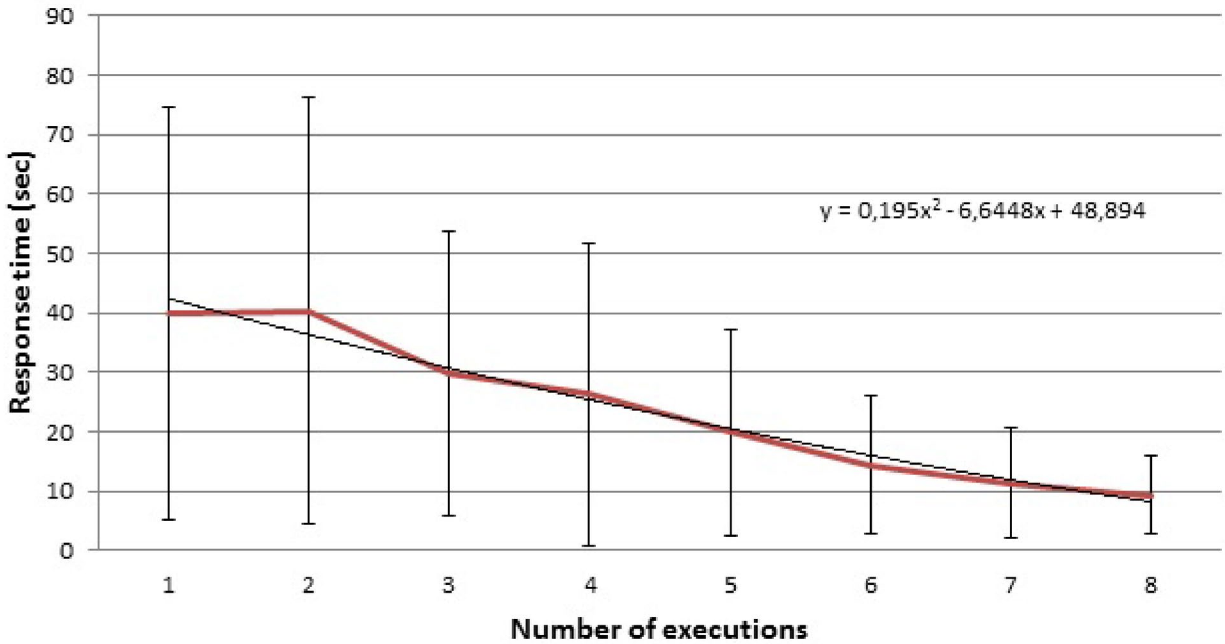

Fig. 19. The reaction times to unexpected events.

The t-test result indicates that the difference between the beginning and the end of simulator use is highly significant ($p < 0.001$), suggesting a systematic change between the two times. The value of Cohen's d, equal to 2.36, represents a very large effect according to the criteria commonly used in literature (0.2 = small, 0.5 = medium, 0.8 = large). The analysis highlights the positive impact of the simulator which produces a significant reduction in errors.

Figure 19 illustrates the reaction times to unexpected events (oxygen loss, fire, compressor block, etc.), demonstrating a significant reduction in response times.

The main limitation of this study is certainly the small number of subjects. Nevertheless, the pilot study described here represents a starting point for future in-depth studies. However, it is interesting to observe the effectiveness of the simulator in reducing the number of errors during the various attempts. From the graphs, an increased initial familiarity with the real hyperbaric chamber can be observed; the simulator does not replace real practice but leads the student to reduce the machine time required to achieve the necessary learning.

Simulator development

We developed a hyperbaric chamber simulator in Java using NetBeans 8, with a MySQL database as the backend. After thoroughly understanding hyperbaric chamber operations, we modelled the relevant physical and biological processes. NetBeans 8 facilitated modular project management and seamless integration of external libraries. We designed an intuitive user interface with Swing, enabling operators to set parameters like pressure and session duration, and to monitor simulated responses. The simulator underwent rigorous testing, with results compared to clinical data to ensure accuracy and reliability. To connect the simulator to the MySQL database, we utilized the MySQL Connector/J driver. This involved adding the connector JAR file to our project in NetBeans, allowing for efficient database interactions. This setup ensured robust data management and storage capabilities for the simulator.

Discussion

Simulation is an effective training modality that has been increasingly used in all fields of medicine in recent years[34]. In the specific area of the use of simulation in hyperbaric medicine, to our knowledge, there are no simulators already in use other than revisions, thus underlining the need for a simulator to be implemented in this field[15]. Moreover, hyperbaric medicine is still not an official speciality in most countries, despite the recent development of knowledge in the field and especially its use in various clinical contexts[35]. The application described in this article could be the first step towards the creation of a simulation in hyperbaric medicine, as to our knowledge, although there is some evidence for the definition of possible scenarios, no actual simulators currently exist[15,36,37].

The developed hyperbaric chamber simulator addresses a critical need in medical training by providing a comprehensive tool for training and simulation for clinical and technical operators in a controlled environment. The software is divided into two main modules: the simulation management module (simulator.jnlp) and the system administration module (manager.jnlp). These modules are accessible through standard web browsers on PCs with the Java Runtime Environment installed.

The simulator's front end offers an intuitive interface for managing various aspects of the hyperbaric chamber, including air and gas flow, lighting, and emergency procedures. The simulation panel is divided into key areas such as the main chamber, equilibrium chamber, and communication and control, each equipped with specific tools and indicators to ensure accurate simulation and monitoring.

The administrative panel (back-end) provides robust tools for user management, including creating, editing, and deleting user profiles, as well as tracking user activity through graphical reports and command logs. The technical specifications section allows for detailed customization of the hyperbaric chamber's parameters, ensuring that simulations can be tailored to specific training needs.

Identifying relevant scenarios is only the first step for creating and implementing a simulation-based curriculum. As a first step to demonstrate the versatility and effectiveness of the simulator, have been identified several simulation scenarios, including generic simulations, simulations with failures (such as fires), and hyperbaric therapy table simulations. These scenarios highlight the importance of proper procedure and the potential consequences of mismanagement, providing valuable training for operators in handling critical situations.

Overall, the hyperbaric chamber simulator is a powerful tool for enhancing training and safety in hyperbaric environments, offering realistic and controlled simulations that prepare users for real-world challenges.

Conclusions

The simulation-based education in hyperbaric medicine here described, will allow teams to train and optimise their practices. Among the various clinical contexts in which to apply simulation, hyperbaric medicine is inherently inter-professional, as it requires close cooperation between different professionals, including doctors from different specialities, chamber operators, technicians, nurses and/or respiratory therapists. If the team is important for routine, it is even more crucial for acute, life-threatening emergency situations, where coordinated actions between the different figures are required. The preliminary quantitative assessments revealed high educational value of proposed simulation software. This technological advancement represents a substantial contribution to hyperbaric medicine education, supporting both initial training and ongoing competency maintenance for clinical and technical operators in this specialized medical field.

As future works, to enhance the hyperbaric chamber simulator, the most impactful improvements would include integrating virtual reality (VR) for a more immersive training experience, developing advanced and customizable simulation scenarios to cover complex emergencies, and implementing real-time performance metrics and automated assessments for immediate feedback. Additionally, enabling multi-user and remote collaboration would facilitate team-based training. Finally, enhanced data analytics and predictive insights, along with regular updates to the scenario library, would further improve training effectiveness.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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Author contributions

M.P. implementation of the web-based training simulator; F.M. writing and modelling of the activities; C.B. writing and modelling of the activities; P.B. writing and modelling of the activities; E.M. writing and modelling of the activities; M.Z. writing and modelling of the activities; M.L. supervisor e design of the study. All authors reviewed the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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