Processor-in-the-Loop (PIL) Simulation of the Proposed Mechanical Medical Ventilator

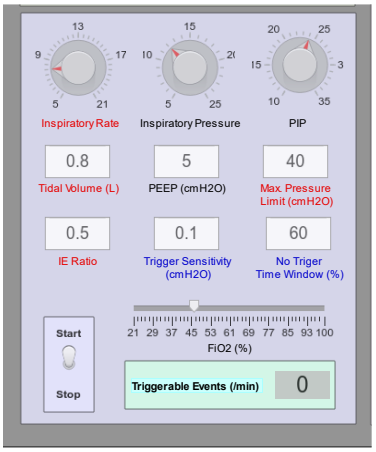
Our first step in the process of developing the mechanical ventilator was to implement a working computational model in the Matlab/Simulink/Simscape environment [1]. As the proof of concept, we managed to successfully simulate several modes of ventilation including Volume Control (VCV) and Pressure Control (PCV), both in Continuous Mandatory (CMV) and Synchronized Intermittent Mandatory (SIMV) modes, and Pressure Support (PSV) and Spontaneous (SP) modes [2]. Further, we have included a patient model in the simulation for testing different scenarios/conditions. As the next step, we embedded the controller module/block of the ventilator on to a microcontroller in order to run the simulation in Processor-in-the Loop (PIL). For this purpose, C2000 LAUNCHXL-F280049C a low-cost development board from the Texas Instruments [3] was used and that will be the motherboard of our prototype ventilator. After successful simulation in PIL mode, we are now in the process of replacing each and every Simulink blocks with their counterpart hardware modules, i.e., to simulate in Hardware-in-the-Loop mode. A brief description about the Simulink model and its PIL simulation is appended next.

1 Simulink Model of the Ventilator

1.1 Modes of Operation

There are 6 modes including default Spontaneous Ventilation Mode.

Mode	Trigger	Target	Cycle Variable
VCV-CMV	Control	Flow rate	Tidal Volume
VCV-SIMV	Assist/Control	Flow rate	Tidal volume
PCV-CMV	Control	Inspiratory Pressure	Time
PCV-SIMV	Assist/Control	Inspiratory Pressure	Time
PSV	Assist	Inspiratory Pressure	Time
SP	No	No	Patient



1.2 User Inputs to the Ventilator

- Inspiratory Pressure (PCV/PSV- as support pressure)
- Respiratory rate
- Tidal volume
- IE Ratio
- PEEP/CPAP
- Trigger Sensitivity (SIMV)
- No trigger window (SIMV)
- PIP
- Maximum Pressure limit
- Oxygen percentage

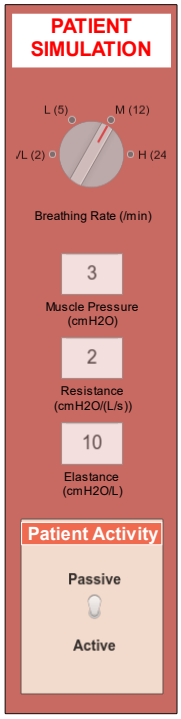
1.3 Automatic Controls for Safety Operation

- PIP cut-off
- Tidal volume cut-off
- Maximum Pressure threshold cut-off
- Control signal for inspiration cut-off/Safety
- Control signal to open expiration valve/Safety

1.4 Alarms to Indicate Limit Exceeds/Reached

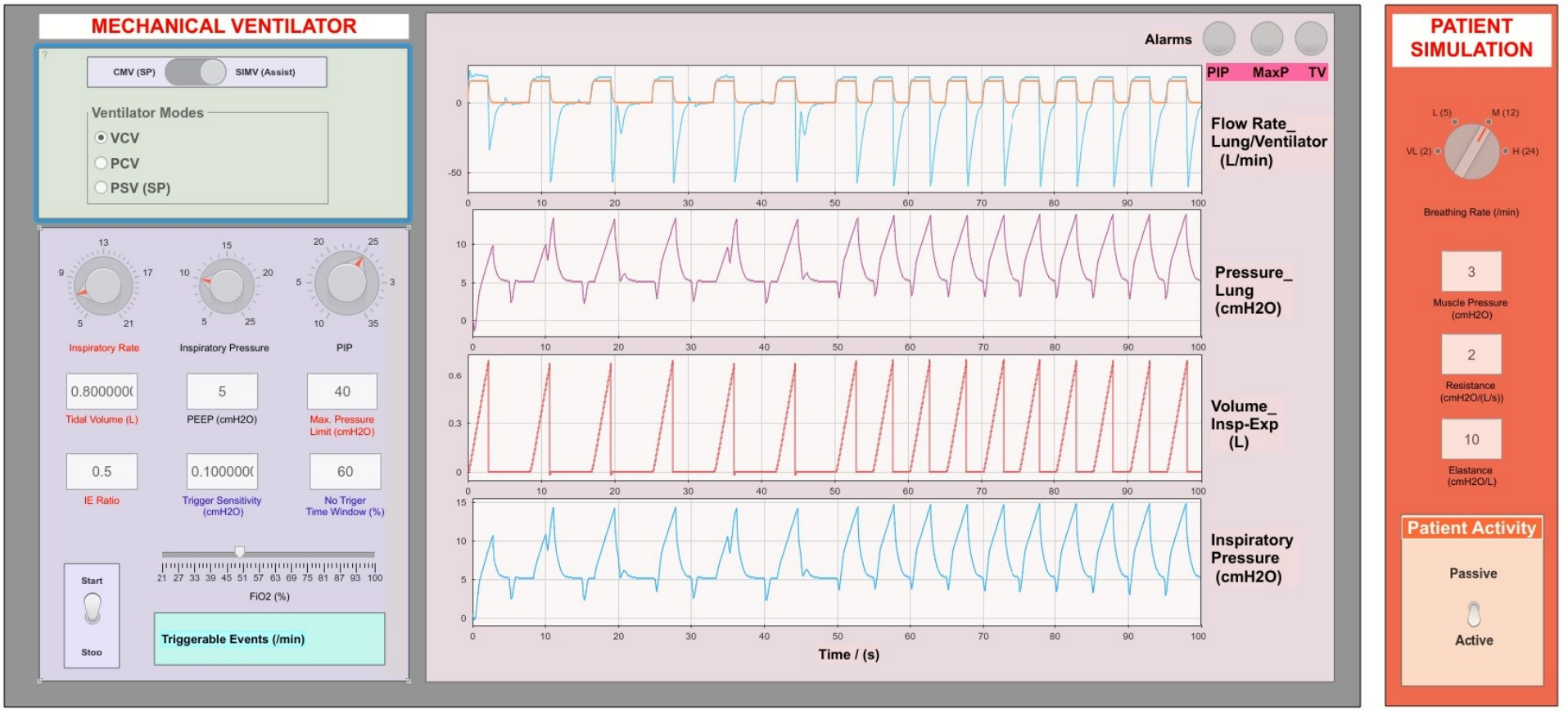
- PIP
- Maximum pressure limit
- Tidal volume

2 Patient Simulation (For Testing Different Conditions)



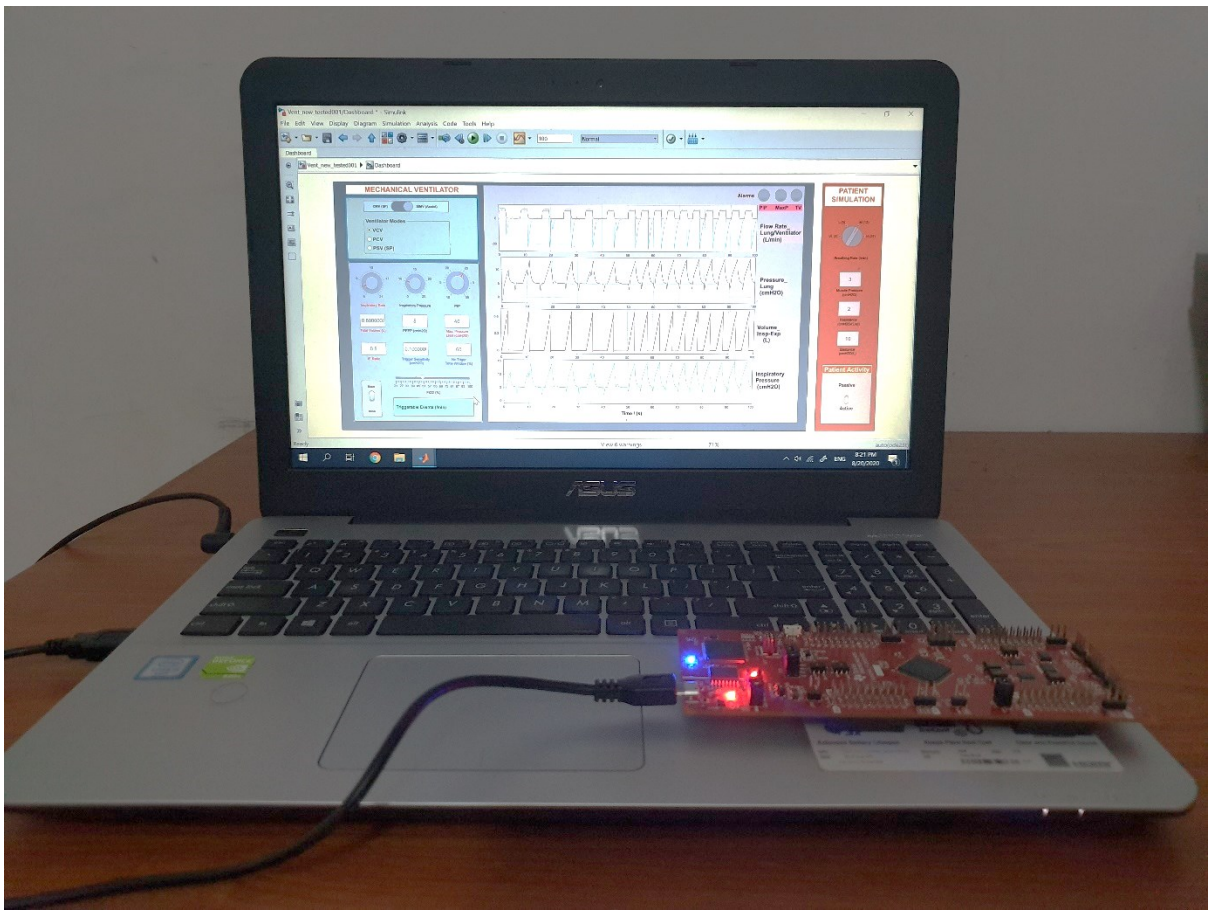
- Breathing rate
- Breathing effort (Muscle pressure)
- Resistance
- Elastance
- Patient activity (Active/Passive)

3 Dashboard to the Simulation (NOT THE DISPLAY UNIT OF THE VENTILATOR)



This shows an example of the ventilator initially running in CMV mode and then switching to SIMV (assist control) in the Volume Control Ventilation. The patient is in active state and do breathing effort in a rate of 12 breaths per minute. The Tidal volume is set at 0.8 l and the PEEP is at 5 cmH2O. The ventilation is set at an IE ratio of 0.5. Trigger sensitivity for the synchronization is 0.1 cmH2O less than the PEEP value.

3.1 PIL Simulation using C2000 LAUNCHPAD Development Board



The C2000 LAUNCHXL-F280049C is a low-cost development board for the Texas Instruments Piccolo F28004x series of microcontrollers (MCUs). It is designed around the TMS320F280049C MCU and highlights the control, analog, and communications peripherals, as well as the integrated nonvolatile memory [3]

4 References

1. *MATLAB 2018a, The MathWorks, Inc., Natick, Massachusetts, United States, 2018*
2. *Tobin, Martin J. Principles and Practice of Mechanical Ventilation. New York: McGraw-Hill Medical Pub. Division, 2013*
3. *User guide, Texas instruments, C2000™ Piccolo™ F28004x Series LaunchPad™ Development Kit 2018*

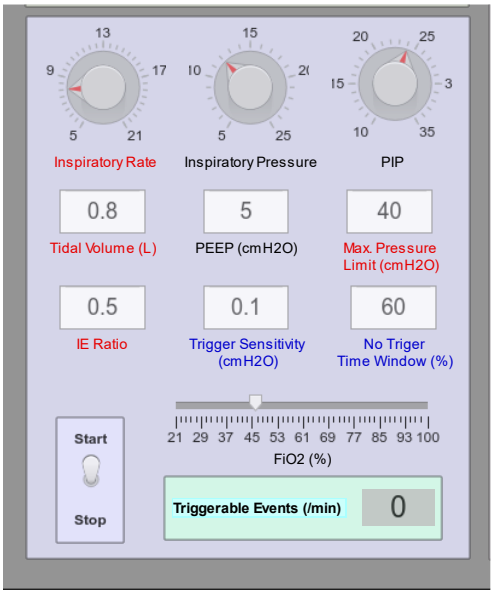
MATLAB Simscape/Simulink Simulation of the Proposed Mechanical Medical Ventilator

Modes of Operation

There are 6 modes including default Spontaneous Ventilation Mode.

Mode	Trigger	Target	Cycle Variable
VCV-CMV	Control	Flow rate	Tidal Volume
VCV-SIMV	Assist/Control	Flow rate	Tidal volume
PCV-CMV	Control	Inspiratory Pressure	Time
PCV-SIMV	Assist/Control	Inspiratory Pressure	Time
PSV	Assist	Inspiratory Pressure	Time
SP	No	No	Patient

Inputs to the Ventilator



- Inspiratory Pressure (PCV/PSV- as support pressure)
- Respiratory rate
- Tidal volume
- IE Ratio
- PEEP/CPAP
- Trigger Sensitivity (SIMV)
- No trigger window (SIMV)
- PIP
- Maximum Pressure limit
- Oxygen percentage

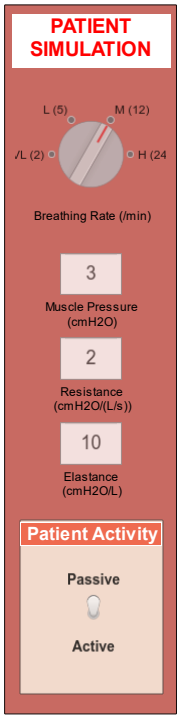
Automatic Controls

- PIP cut-off
- Tidal volume cut-off
- Maximum Pressure threshold cut-off
- Control signal for inspiration cut-off/Safety
- Control signal to open expiration valve/Safety

Alarms

- PIP
- Maximum pressure limit
- Tidal volume

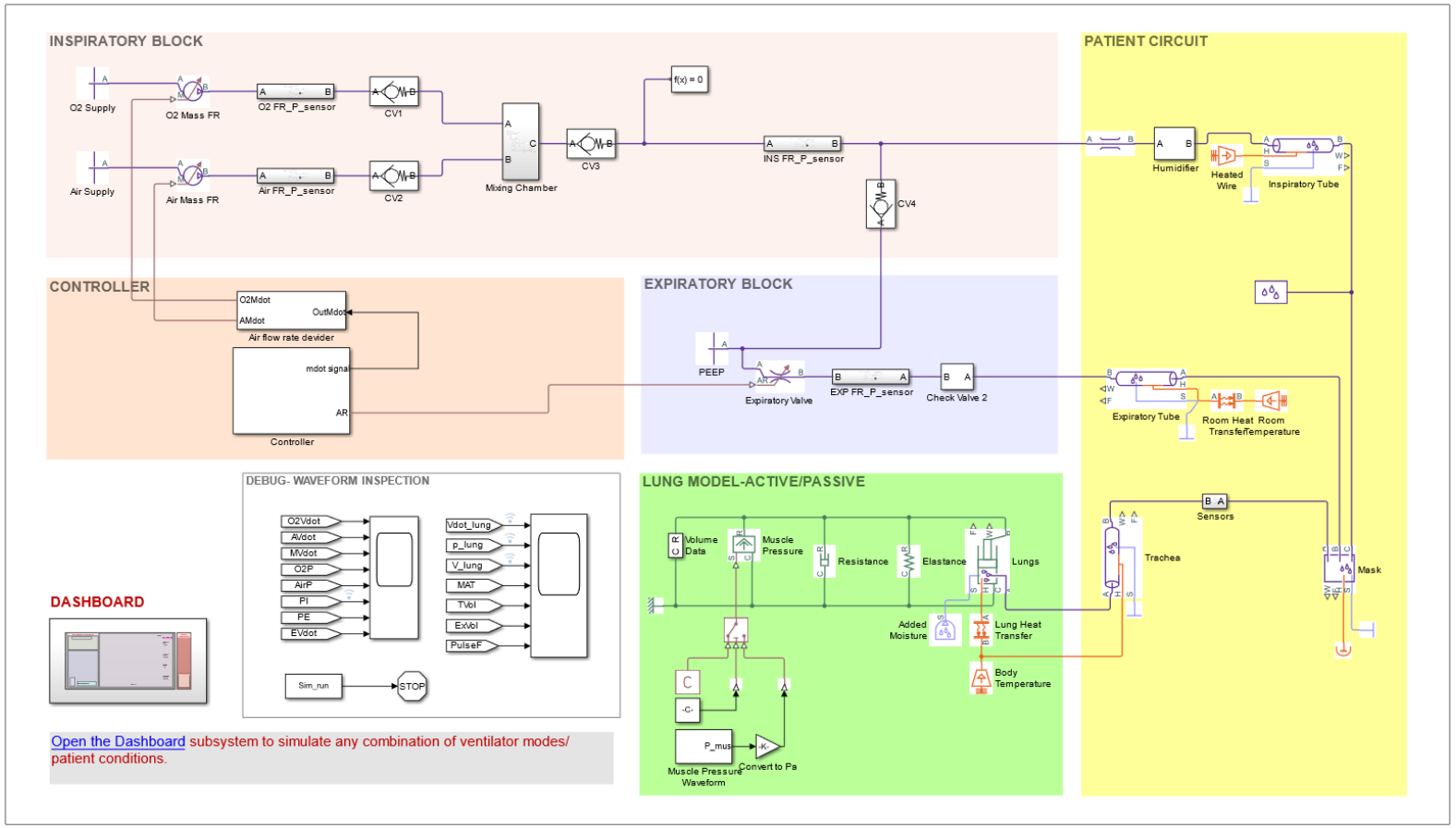
Patient Simulation



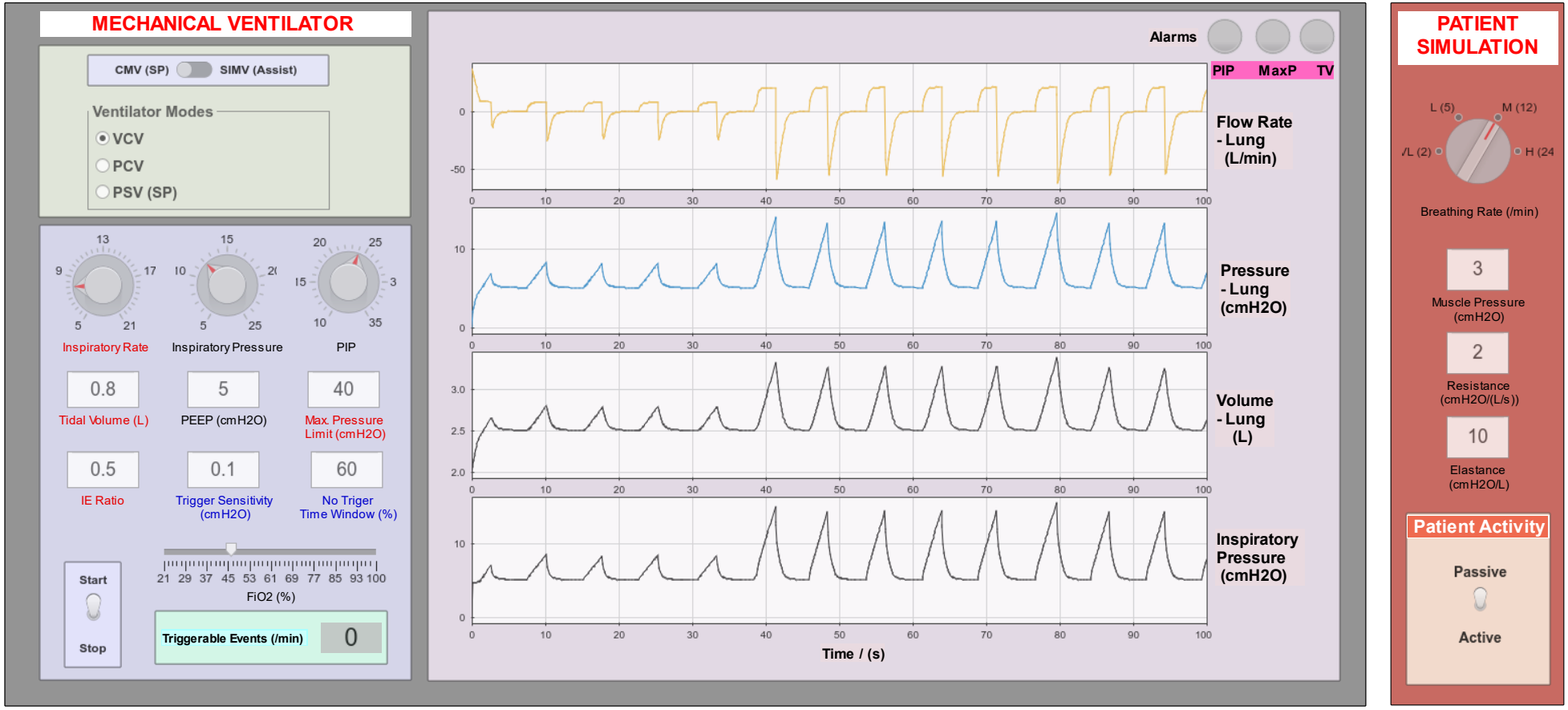
- Breathing rate
- Breathing effort (Muscle pressure)
- Resistance
- Elastance
- Patient activity (Active/Passive)

Block Diagram of the Simulated Modules

Ventilator	Patient Circuit	Waveform inspection
➢ Inspiratory block ➢ Expiratory Block ➢ Controller	Lung model	Dashboard (NOTE: User interface to the Simulation- NOT the DISPLAY UNIT of the proposed ventilator)



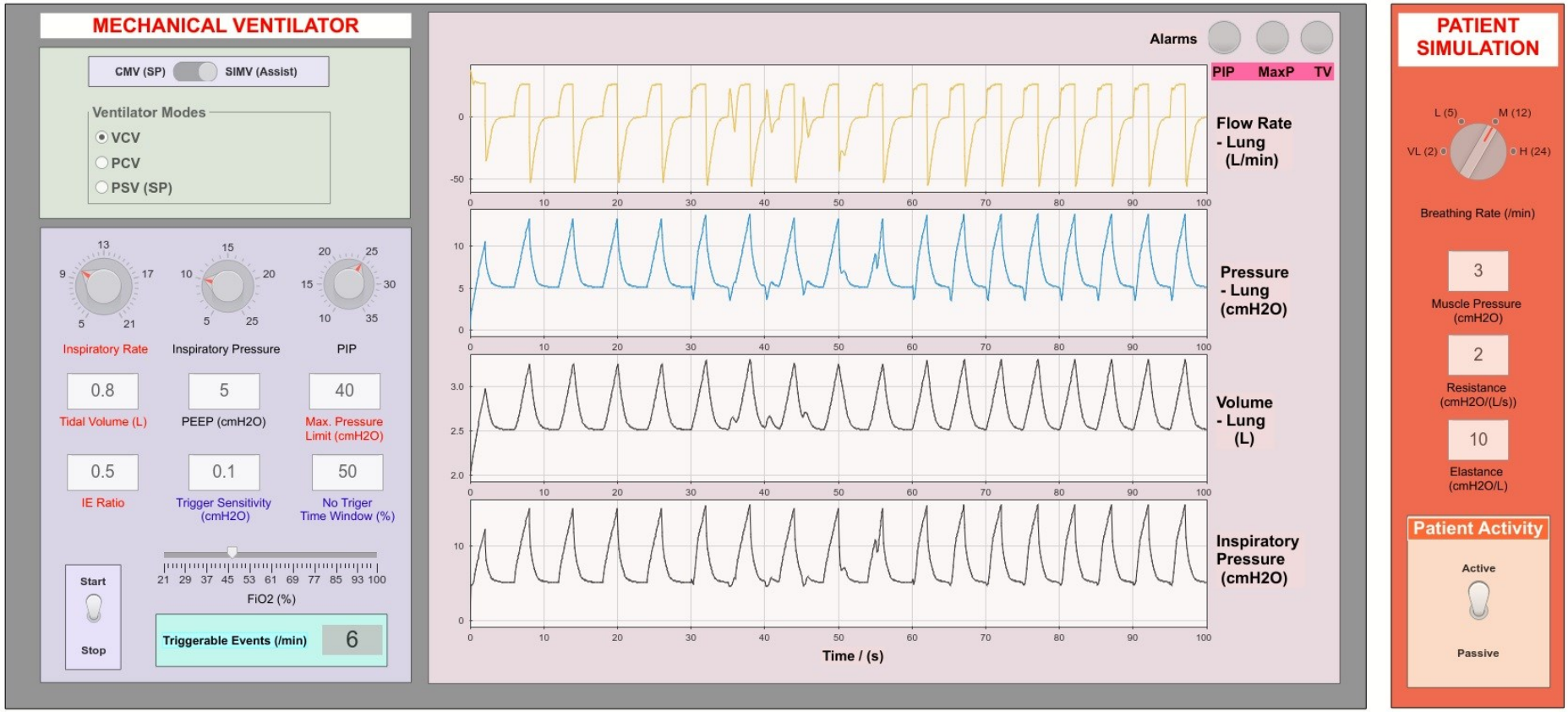
Dashboard to the Simulation (NOT THE DISPLAY UNIT OF THE VENTILATOR)



Results

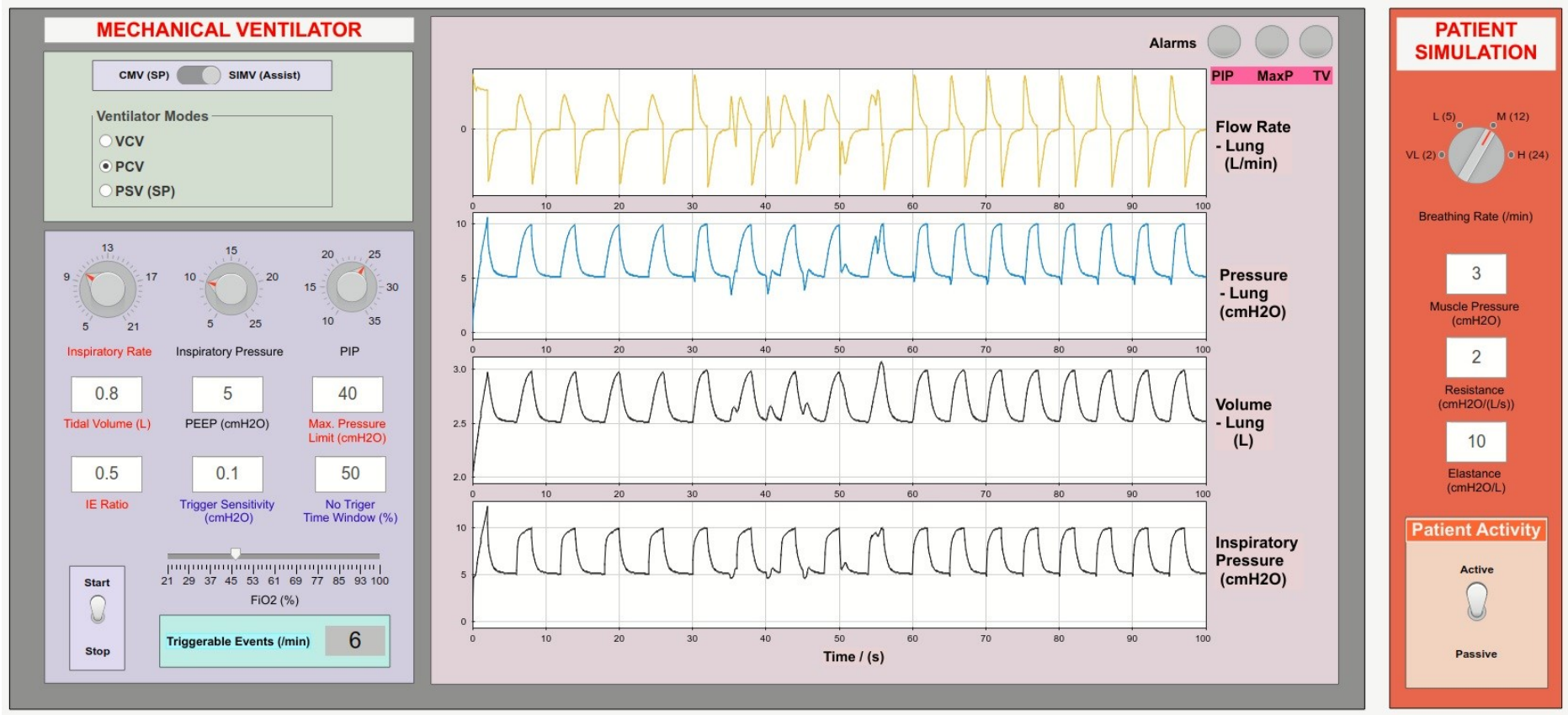
VCV Mode

- About First 1/3rd - VCV-CMV with a Passive patient
- Second 1/3rd VCV-CMV with an Active Patient
- Third 1/3rd VCV-SIMV



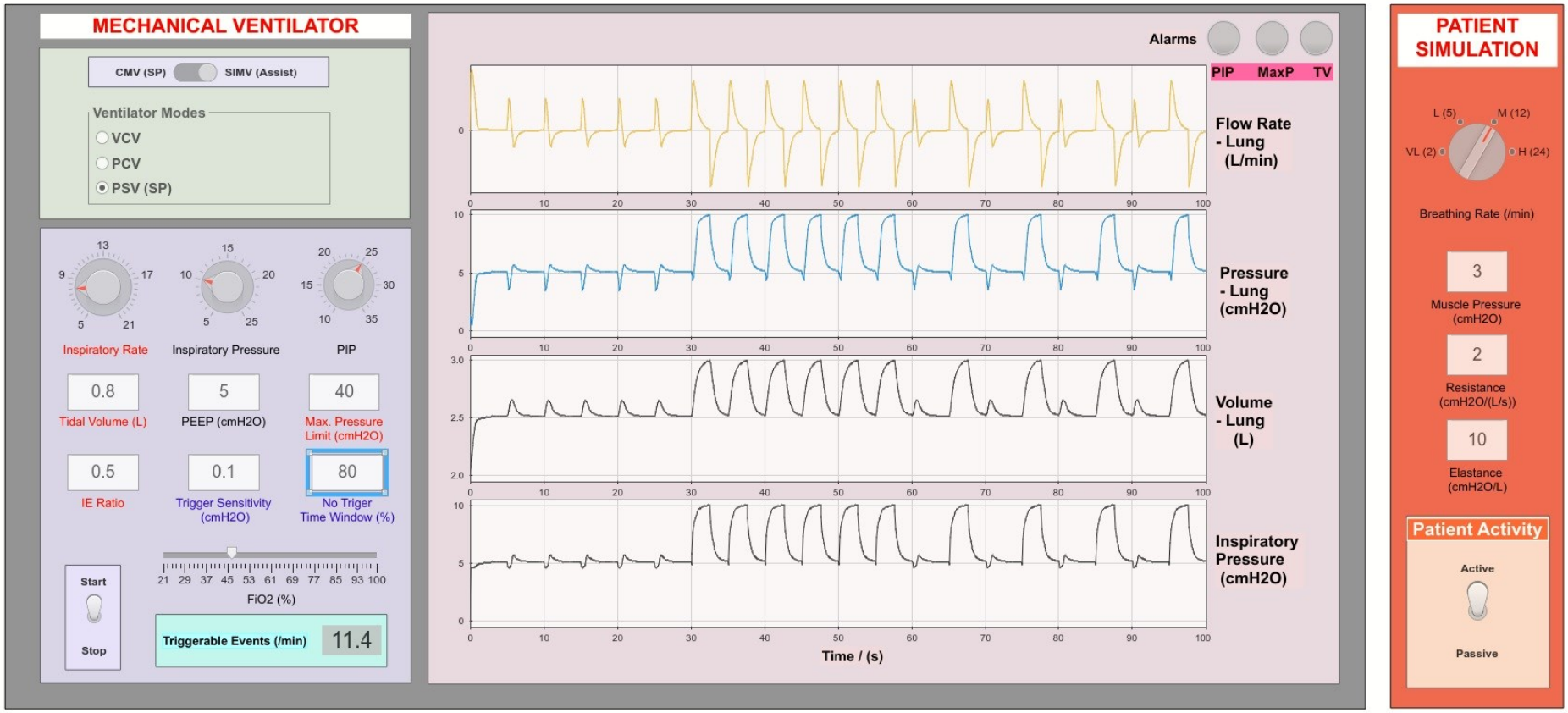
PCV Mode

- About First 1/3rd - PCV-CMV with a Passive patient (first couple of seconds is VCV)
- Second 1/3rd PCV-CMV with an Active Patient
- Third 1/3rd PCV-SIMV



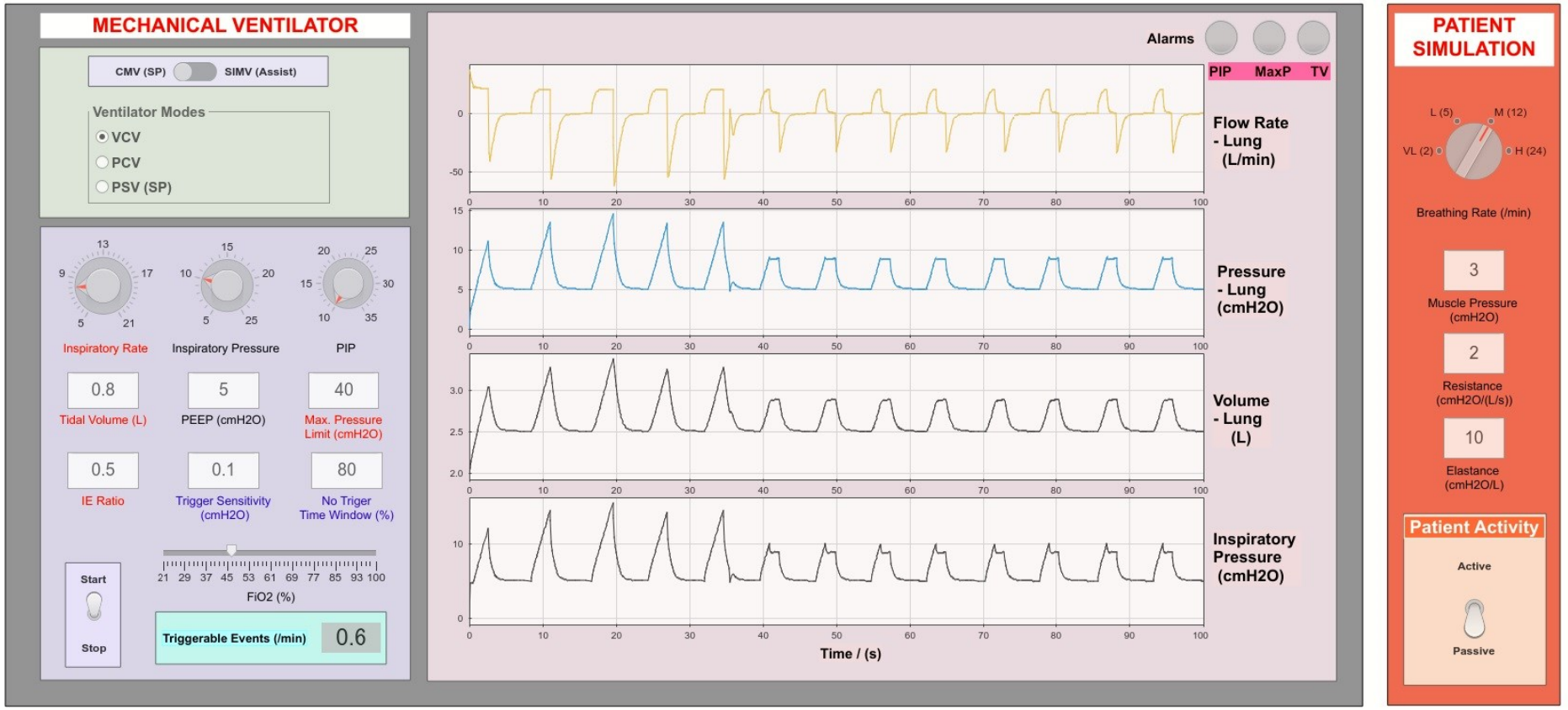
PSV/SP Mode

- About First 1/3rd - SP Mode
- Second 1/3rd PSV with NO trigger 50%
- Third 1/3rd PSV with NO trigger window 80%



VCV with PIP in action

- Initially PIP is about 25 cm H2O and then reduced to 10 cmH2O



PCV with different Tidal volume limits

- About First 1/3rd - TV = 0.8 L
- Second 1/3rd – TV = 0.5 L
- Third 1/3rd - TV = 0.3 L