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# Design of a unidirectional valve for mechanical respirator duplicator, during Covid-19 times in Colombia

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**Abstract**

One of the consequences of coronavirus (covid-19) in the planet is the possible lack of mechanical respirators in Intensive Care Units (ICU) in different healthcare providing facilities, especially in those regions where there is no ICU availability and coronavirus (covid - 19) infections are high, such situation could cause a collapse of the health system, that is why the Department of Mechanical Engineering, New Engineering Technologies Research and Development Group (GIDINT) of the Santo Tomás Aquino University - Tunja, Colombia, has carried out the design, development, and analysis of a duplicator for mechanical respirators using 3D printing as a manufacturing method, which by means of a unidirectional valve allows the flows gas for both expiration and inspiration through dedicated ducts, thus, guaranteeing the a correct mechanical respirator's operation and ensuring that patients' health is not put at risk during its use. This piece of medical equipment can be used as a last resort in case there may not be enough mechanical respirators available in healthcare providing facilities during an emergency caused by coronavirus (covid - 19).

**Keywords:** Design, analysis, duplicator, 3D printing, coronavirus, mechanical respirator.

## I. INTRODUCTION

Colombia, like many countries, took actions to contain coronavirus (covid - 19) and answer the needs of the general population. However, thanks to the high impact that this emergency has generated in the healthcare systems, it is necessary to think about strategies that can help solve the shortage of medical equipment in healthcare providing facilites.

One of the complications associated with the covid-19 virus is the patient's respiration and oxygenation process, which is currently being addressed through the use of mechanical respiration necessary for the patient's life support.

Taking the current availability of respirators available to healthcare facilities and the high number of infections into account, the possible collapse of intensive care units is a possibility, which is why the use of multiple mechanical or multi-pulmonary respiration is proposed in order to better take advantage of the currently available resources.

For the research group, the use of individually mechanical respirators is essential, analyzing the situation a local perspective it is evident that Boyacá hasn't enough respiratory resources to provide care for all the patients who will be possibly affected by the Covid–19 virus.

Taking this problem into account, it is necessary to implement strategies that allow to reduce the impact of this emergency, therefore, the use of shared or multi-pulmonary mechanical respiration is proposed aiming to mitigate the problem's effects during the health emergency generated by the virus and the high volume of patients in ICUs.

The basis for the project is a standard respirator, its diagram is shown below:

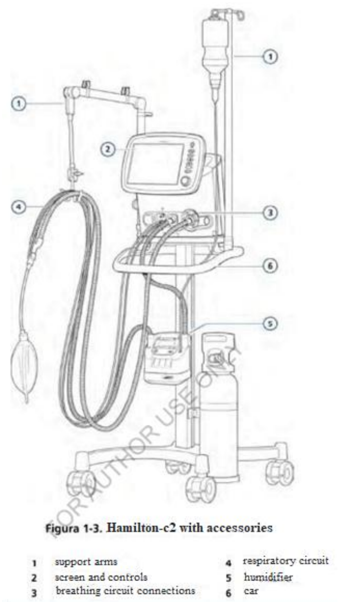


**Fig. 1.** Mechanical respirator's componets.
Source: Taken from the HAMILTON-C2 respirator user's manual.

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## II MECHANICAL RESPIRATION

Mechanical respiration is supplied by devices that intend to provide life support to patients who cannot breathe on their own or who need assistance, these devices move air and/or oxygen to and from the patient's lungs. This assistance is given in different cases such as disease, trauma, congenital diseases or while under the influence of drugs such as anesthesia.

Mechanical respiration can be delivered non-invasively by means of a respirator mask or helmet. Or invasively through endotracheal intubation for patients who cannot protect their airways, such as those in a coma, this technique can also be applied under the doctor's discretion when the patient is condition is expected to worsen or during airborne pathogen infections. (Assesment, 2020).

The concept of artificial respirator was coined by Vesalius in 1555, but in 1928 Drinker and Shaw, used the first iron lung which was later perfected by Emerson in 1950, during the Poliomyelitis epidemic the use of this therapeutic technique was widely required. Two years later Engstrom introduced positive pressure respirator from which many of the current mechanical respiration’s theories and models come from. (Colice, 2006).

For a gas to flow, there must be a positive pressure gradient which is defined as the force exerted on a surface to displace a volume, which depends on the resistance and the distance the gas is going to travel. For mechanical respiration there are four types of pressure which are: (Loeches, De Haro, Dellinger, Ferrer, & Levy, 2013):

- Peak inspiratory pressure (PIP): it is the maximum pressure obtained during the distribution of an active gas.
- Plateau pressure: it is the final inspiratory pressure during a period of gas flow absence.
- Average airway pressure: it is the average pressure during the respiratory cycle (inspiration and expiration).
- End-expiratory pressure: it is the airway pressure at the expiration’s end phase and is normally equal to atmospheric pressure.

A functioning mechanical respirator’s pressure can be measured in different places within the ventilatory cycle, there is also a flow which refers to the speed at which a volume of gas is delivered per unit of time in two points of a duct. Thanks to the pressure gradient this flow is translated to liters per minute (Ortiz, Dueñas, Lara, Garay, & Blanco, 2013).

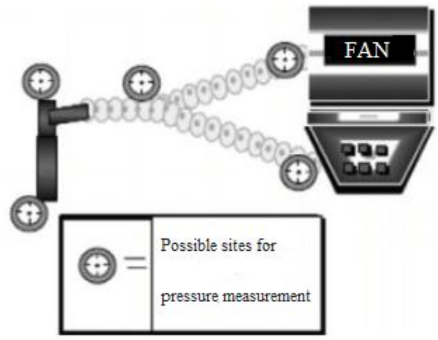


**Fig. 2.** Places in which to measure the respirator.
Source: Butcher & Boyle, 2016.

In the Y shaped piece in the ventilatory circuit, in the opening of the airway, in the carina, by applying a pressure control line to a tracheal tube with an extra lumen.

### II.I Monitoring of mechanical respiration

It is important monitor what happens between the patient and the respirator constantly using basic and advanced monitoring methods (Hernandes & Triolet, 2002) or multimodal monitoring.

| **General monitoring** | **Images:** |
|---|---|
| * Neurological status | * Chest x-ray |
| * Respiratory status | * TACHM Thorax |
| * Cardiovascular status | * TAC electrical impedance |
| * kidney status | * Pulmonary ultrasound |
| * gastrointestinal status | |
| **Respiratory monitoring** | |
| Respiratory parameters | Gas exchange |
| * $FIO_2$ | * Arterial blood gas |
| * Breathing frequency | * Pulse oximetry |
| * volume | * Capnography |
| * Ratio I: E | * Volumetric capnography |
| * Pressures | * $SvO_2$ |
| * PEEP | |
| * Flow | |
| * Sensitivity | |
| * Dead space | |
| * Alarms | |
| * Humidity and T | |
| * Spirometry | |
| Lung mechanics | patient-ventilator synchrony |
| * Respiratory work | * Patient |
| * Complacency | * Fan |
| * Endurance | * Sensitivity |
| * Occlusion pressure | |
| * Flow, volume and pressure curves over time | |
| * Loops P / V - F / V | |
| * Tracheal pressure (transpleural) | |
| * Esophageal pressure | |

**Figure 3.** Respiratory supported patien’s monitoring
Fuente Gutierrez Muñoz, 2011

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### II.II Design, construction and analysis of the mechanical respirator's duplicator

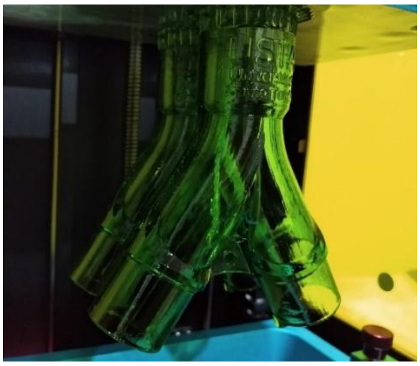

**Fig. 4.** Duplicator construction
Source: Authors

In an ideal world, no doctor who treats patients with acute respiratory distress syndrome (ARDS) would have to connect several patients to a single mechanical respirator, however the current COVID-19 pandemic is making health professionals go around the world take extreme measures in the most affected regions, meaning that they will have to find a balance between available resources and the resources required to care for all patients making the option of connecting multiple patients to a single respirator a viable one (Branson, Blakeman, Robinson, & Johannigman, 2012).

### II.III Materials and Methods

The duplicator is made up of a series of accessories used to address the possible shortage of respirator devices in hospitals, which is becoming a specific problem related to the spread of COVID-19. It was determined that the best way to manufacture these elements is 3D printing, given the mandatory preventive isolation decree issued by the national government. The use of these 3D printing equipment does not require a lot of space and using the right settings and calibrations, good products are manufactured.

The Santo Tomás University in Tunja acquired the following equipment and materials to manufacture and implement the duplicator prototype:

### II.IV Duplicator design

For the design of the duplicator, the output connectors' dimensions that go from the duplicator to the respiratory circuits were measured, the external diameters of the two duplicator outputs are 22 mm and the internal diameters are of 19mm, for a male connection. For the design of the respirator duplicator's connection, the dimension of the external diameter of the tube were taken, it has an internal diameter of 22 mm, and an external diameter of 25 mm, for a female duplicator. The design was made using the Inventor Software.

**Fig. 5.** Duplicator for a mechanical respirator.
Source: Authors

For the construction of the duplicators, a Anycubic Photon S resin 3D Printer was used, and for the construction the Ultraviolet Resin 405nm 500ml was used.

### III RESULTS

The oxygen supply for a mechanically ventilated patient is approximately $\frac{6\,ml/s}{kg}$. If we consider two patients with a mass of 100 kg each, we have a total mass of 200 kg and the volumetric flow of total oxygen [Q] is:

$$Q = \frac{6\,ml/s}{kg} \times 200kg = 1200\,\frac{ml}{s} = 1.2 \times 10^{-3}\,\frac{m^3}{s} \qquad (1)$$

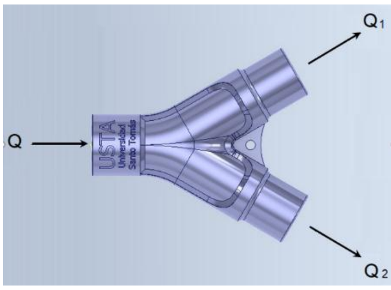


**Fig. 6.** Inflow and outflow in the duplicator.
Source. Authors

By continuity equation (law of conservation of matter), we have that: $Q = Q_1 + Q_2$
But the flow in the duplicator is symmetric; this means that: $Q_1 = Q_2$
From the two previous equations it is concluded that:

$$Q_1 = Q_2 = \frac{Q}{2} = \frac{1.2\times10^{-3} m^3/s}{2} = 6 \times 10^{-4}\,\frac{m^3}{s} \qquad (2)$$

To determine the density (ρ) of oxigen ($O_2$), it is required to know the absolute pressure at which it is. Maximum positive pressure ($P_m$) in each patient 35 cm of in the water column equal to:

$$P_m = 35\ cm_{H_2o} \times 1 \frac{m}{100\ cm} \times 9810 \frac{N}{m^3} = 3.433 kPa \quad (3)$$

Atmospheric pressure ($P_{atm}$) in the city of Tunja it is at 550 mm in the mercury column, which equals to:

$$P_{atm} = 550 mm_{Hg} \times \frac{101325 Pa}{760 mm_{Hg}} = 73.327\ kPa \quad (4)$$

The absolute pressure (P) is the sum of the two calculated pressures: $P = P_m + P_{atm} = 76.76$ kPa

The average temperature of the $O_2$ to be supplied is set at T = 25 ˚C = 298 K

With the previous considerations of temperature and pressure, oxygen is considered as an ideal gas, because it is in a very distant state from its critical point (154.8 K and 5.08 MPa), data obtained from table A1 reference [1]. Therefore, $O_2$ complies with the ideal gas state equation:

$$\frac{P}{\rho} = RT \rightarrow \rho = \frac{P}{RT} \quad (5)$$

In Aable A-1 of reference [2] we have that the gas constant of oxygen is $R = 0.2598 \frac{kJ}{kg \times K}$

$$\rho = \frac{76.76\ kPa}{0.2598 \frac{kJ}{kg \times K} \times 298 K} = 0.991 \frac{kg}{m^3} \quad (6)$$

In table A10 (Cengel Y. A., Cimbala J.M, 2006), the dynamic viscosity of $O_2$ at 1 atm pressure and 25 ˚C is : $\mu = 2.221 \times 10^{-5} \frac{kg}{m \times s}$

In figure D1 of reference [3] a very similar result is graphically obtained for the viscosity of oxygen as a function of temperature. .

Reynolds number ($N_R$) is the dimensionless parameter that allows to establish if a flow is laminar or turbulent, or if it is in a transitory state (not desirable because the level of uncertainty is maximum and its behavior cannot be predicted).

$$N_R = \frac{\rho V D}{\mu} \quad (7)$$

In the equation V is the average velocity of the flow and D is the internal diameter of the section perpendicular to the flow.

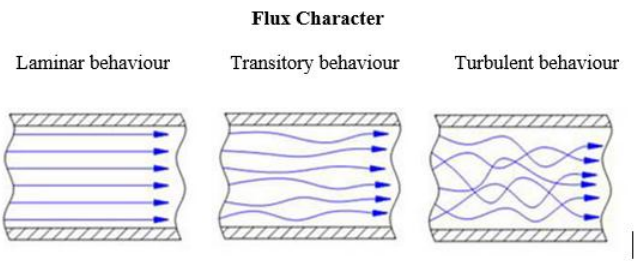


**Fig. 7.** Types of flow in a duct.

In the duplicator there are different flow areas as can be seen in figure 8.

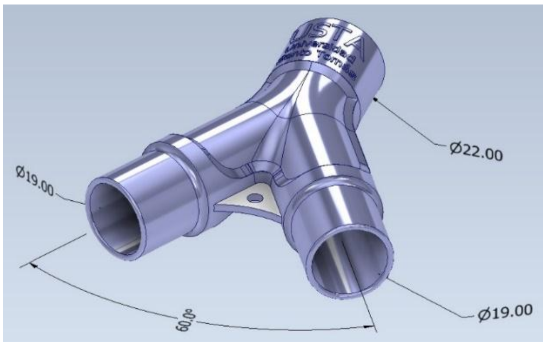


**Fig. 7.** Detail of the internal inlet and outlet diameters in the duplicator.
Source. Authors

The internal or flow area at the inlet of the duplicator is determined according to:

$$A = \frac{\pi \times D^2}{4} = \frac{\pi \times (0.022m)^2}{4} = 3.8 \times 10^{-4} m^2 \quad (8)$$

The speed V at the input of the duplicator is:

$$V = \frac{Q}{A} = \frac{1.2 \times 10^{-3} m^3/s}{3.8 \times 10^{-4} m^2} = 3.16 \frac{m}{s} \quad (9)$$

With the results obtained, the Reynolds number is determined at the input of the duplicator:

$$N_R = \frac{0.991 \frac{kg}{m^3} \times 3.16 \frac{m}{s} \times 0.022m}{2.221 \times 10^{-5} \frac{kg}{m \times s}} = 3101.95 \quad (10)$$

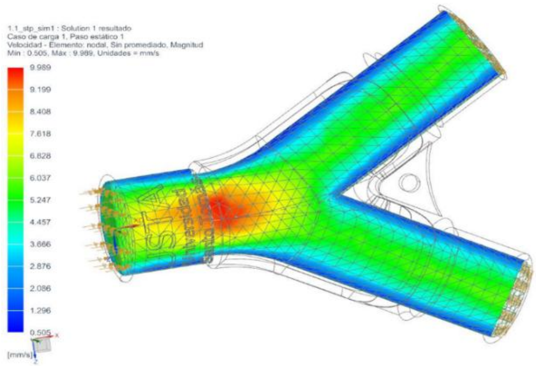

**Fig. 9.** Flow simulation before division.
Source: Authors

The flow at the inlet of the duplicator is in the transition zone because $2000 < N_R < 4000$, as seen in figure 8. The reason can be attributed to the fact that the incoming flow is twice the normal flow for which the duct diameters of the unmodified equipment were originally designed.

At the outlet of the duplicator, the flow is divided into two branches with cross sections of the same size. The internal or flow area at the outlet of each branch of the duplicator is determined according to:

$$A_1 = A_2 = \frac{\pi \times D^2}{4} = \frac{\pi \times (0.019m)^2}{4} = 2.835 \times 10^{-4} m^2 \quad (11)$$

The speeds $V_1$ y $V_2$ at the exit of each branch, also equal to:

$$V_1 = V_2 = \frac{Q}{A} = \frac{6 \times 10^{-4} m^3/s}{2.835 \times 10^{-4} m^2} = 2.117 \frac{m}{s} \quad (12)$$

With the previous results, the Reynolds number is determined, which is the same for the two branches:

$$N_{R1} = N_{R2} = \frac{0.991 \frac{kg}{m^3} \times 2.117 \frac{m}{s} \times 0.019m}{2.221 \times 10^{-5} \frac{kg}{m \times s}} = 1794.73 \quad (13)$$

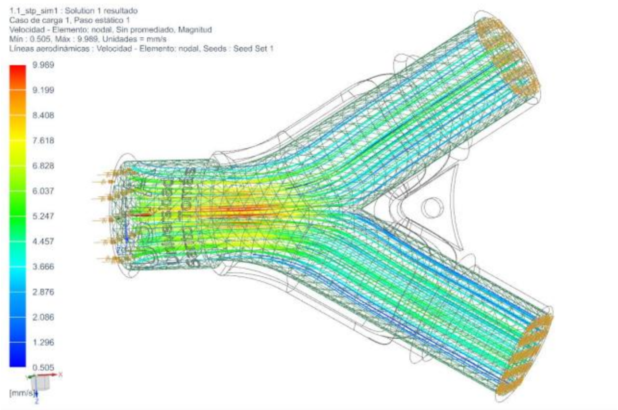


**Fig. 10.** Simulation of laminar flow in the branches.
Source: Authors

At the outlet of each branch, the flow is laminar as shown in figure 9, because $N_R < 2300$. Although it is relatively close to the maximum laminar flow value, it is important to bear in mind that the calculations were made for two people weighing 100 kg each. For people who weigh less, it is guaranteed that the flow will be even more laminar.

The reference velocity limit layer analyzes [2] establish that the hydrodynamic region is fully developed when the flow travels the hydrodynamic inlet length ($L_{h,\ laminar}$) which for laminar flow is determined according to:

$$L_{h,laminar} \approx 0.05 \times N_R \times D = 1.7m \quad (14)$$

According to the previous calculation, it is recommended that each duct that goes from the duplicator outlet branches to the connections with the patient, have a minimum length of 1.7m, to avoid feeling the effects of shear stresses in the flow. , caused by the viscosity of gas.

The final diagram of the respiration circuit using the mechanical respirator duplicator is illustrated in figure 10:

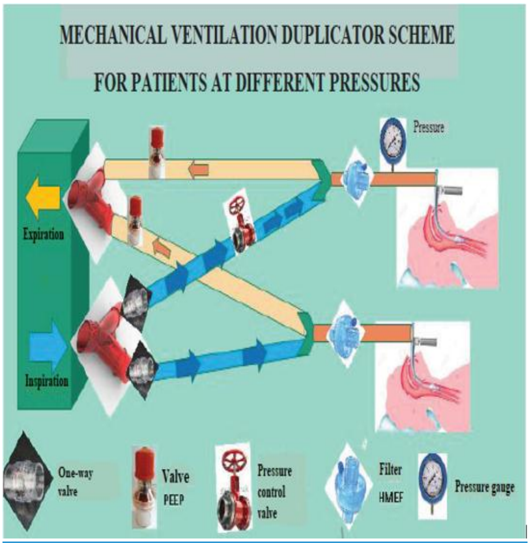


**Fig. 11.** Mechanical respirator's duplicator schematic for patients set at different pressures.
Source: Authors

1. Hamilton G5 mechanical respirator or similar equipment Draeguer, Pruritan Bennet, Avea, Servo i (This will be the respirator used in the tests, however, the data on the types of respirators the department is pending).
2. Two 3D printed duplicators (manufactured by USTA Engineering Group).
3. Two anesthesia circuits with Y and test balloon.
4. Two inspiratory and expiratory valves (depending on the type of respirator to be used).
5. 5. Two unidirectional valves.
6. Two low pressure transducers.
7. Two luer port connectors.
8. Two HEPA filters and two HMEF FILTERS.
9. A portable capnograph and/or capnography line for the monitor.
10. Respirator cart.
11. Ambu, manual resuscitator or self-inflating bag.
12. High pressure oxygen canister.

## IV CONCLUSIONS

The use of 3D printers is of great help in these cases since they do not require specialized personnel for their management, nor a large infrastructure for their operation and provides a high-quality final product.

At the inlet of the duplicator, the oxygen flow becomes turbulent because the amount of oxygen that is coming out of the respirator is over the amount for which the outlet is designed.

The implementation of the mechanical respiration duplicator does not affect the flow of oxygen to the patient, since at the exit of each branch the flow continues to be laminar, which is ideal for these cases.

This duplicator was is to be used a last resort since additional protocols are required for its correct operation and reduction of the patients' risk.

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