CHEAP EASY ASSEMBLY PANDEMIC REPIRATOR

CEA-PR

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Contents

1 Abstract

This project proposal aims to stimulate the discussion and the work on different models of very traditional and simple pandemic respirators that are simple Ambu actuators that can be manufactured also in poor countries with very traditional technologies. The ventilation process should be tightly controlled, an uncontrolled pressurization could harm the patient badly and could lead to serious internal injury. This is a preliminary research looking into medical complications of mechanical respiration and improvising the Cheap Easy Assembly Pandemic Respirator (CEA-PR) design in the field of control.

2 Hypothesis

The CEA respirator is a motor-operated device, primarily the torque and rpm required to run the machine is an essential value. RPM can be calculated on the basis of no of breathing cycles required in a minute, working out force with help of torque value will help in determining other values. Power of motor can be determined by force and angular velocity.

Compression of Ambu bag plays an essential role in flow rate control, compression can be controlled by force applied pressure control is essential for tidal volume. Both force and pressure can be calculated by velocity and rotating armlength of machine.

Minimum force required to compress the Ambu bag can be identified by using Ideal Gas Law, by identifying internal pressure internal force can be identified. In this case applied force can be assumed greater than the internal force, and further compression calculation can be made. After calculating all the major values pressure, force and RPM can be calculated for execution of a controlled flow rate and tidal volume according to the patient.

3 Theory

3.1 Medical Point of View

Mechanics of breathing does not allow lungs to inflate like a balloon, when a person breathes his diaphragms contracts along with the intercostal muscles. Which increases the thoracic cavity (the cavity in which lungs resides), this causes increase in volume and decrease in pressure. To equalize the pressure, the lungs expand and equalizes the atmospheric pressure. Hence breathing is control by two muscle groups. The key thing here is that negative pressure initiates the process of inhalation. The exhalation process is exactly reverse of this process, with a small spike above atm to push the air out of the system.

On the other hand, the mechanical ventilation forces the air into the lungs from outside the body and blow lungs like balloon, if this process is not tightly controlled, the air pressure could work against the primary breathing muscles diaphragm and intercostal. This situation could lead to increasing the pressure in the alveoli (over expanding), above their maximum pressure.

Alveoli are the tiny air sacks present in the lungs that are in contact with blood vessels, they are responsible for O2 and CO2 exchange, and diffusion of O2 in the blood. They are very delicate pieces of tissue. The most damage over pressurization could cause is least inflammation, worst rupture. This situation is called Barotrauma. Patients affected by COVID19; in more severe cases it is associated Acute Respiratory Distress Syndrome (ARDS) are more prone to this side effect of mechanical ventilation. The high-end ventilation devices are also controlled very carefully by experienced Doctors, in expensive ventilators the breathing sequence is triggered by the patients.

Other injury due to over pressure, Air to inflate the stomach (gastric insufflation), Lung injury from overstretching (volutrauma).

3.1.1 Tidal Volume

Tidal volume is the air displaced between inspiration and expiration, when no external effort is applied. For a healthy young adult tidal volume is approximately 500 ml per inspiration or 7 ml per kg of body mass. Patients without pre-existing lung disease, $V_T = 6\frac{ml}{kg}\ to\ 8\frac{ml}{kg}$ and Respiration rate is 12 to 20 breaths/ min.

Patients with chronic obstructive lung disease requires high enough rate for proper alveolar ventilation, in this case protective lung ventilation applies which ranges from, $V_T = 6\frac{ml}{kg}\ to\ 8\frac{ml}{kg}$ and instinct peep does not create. With ARDS the lung tissues are very vulnerable, permissive hypercapnia technique is applied. In severe cases 5 ml/ kg tidal volume is applied, PH avoids the delivery of high inspiratory pressures and lower the tidal volume. In this situation a higher PEEP is applied, however different types of PEEP levels are required for different situations.

3.1.2 Flow rate

Working out the flow rate for average weighting adult. The average tidal volume is approximately 500 ml per inspiration or 6 to 8 ml/ kg. Normal frequency of breath is 5 to 6 sec per breath, approximately 12 breath per minute. So, calculating flow rate of a 75 kg patient,

$$Flow\ rate = Tidal\ Volume\ /kg * Respiration\ rate$$ *Equation 1*

Protocol states that 15 L/ min flow rate is normal. Keeping control of tidal volume is also important because a higher tidal volume higher than 10 ml/kg increases risk of pulmonary barotrauma.

3.2 Engineering point of View

Control of rpm can control compression and volume.

So,

$$RPM = \frac{Number\ of\ Revolution}{Time\ (in\ minutes)}$$ *Equation 2*

Speed of the motor is defined for a selected breathing rate, by using rpm value the angular velocity can be calculated,

$$Angular\ velocity\ (\omega) = \frac{RPM}{60\ sec/min} * 2\pi\frac{rad}{rev}$$ *Equation 3*

Linear speed can be calculated by using angular velocity,

$$v = \omega * r$$ *Equation 4*

Power can be calculated by,

$$Power\ (P) = Torque(\tau) * AngularVelocity\ (\omega)$$ *Equation 5*

The calculations present here are theory based, to identify the force applied and power required, first it is the force present inside can be identified. When force and pressure applied will be greater than the inside pressure and force the compression will occur.

For calculating force by using power applied,

Power relates to force and velocity; power is rate of work done,

$$P_{avg} = W * \Delta_t \quad \text{Equation 6}$$

Work and force have a relation, in our case work done at a constant force,

$$W = F_X \Delta_X \quad \text{Equation 7}$$

where,

F_X is force in x direction, Δ_X is displacement.

Putting values in, $P_{avg} = W * \Delta_t$ Equation 6

$$P_{avg} = \frac{F_X \Delta_X}{\Delta_t}$$

$$P_{avg} = F_X \frac{\Delta_X}{\Delta_t}$$

where,

$$\frac{\Delta_X}{\Delta_t} = V_{avg}$$

so,

$$P_{avg} = F_X V_{avg}$$

More general outcome or other way,

$$P = \vec{F} * \vec{V}$$

$$P = F * V \cos(\theta)$$

If the force and velocity are in the same direction than angle is 0,

$$\cos(0) = 1$$

So,

$$P = F * V \quad \text{Equation 8}$$

Pressure applied (P_{app}) can be calculated by,

$$P_{app} = \frac{F}{A} \quad \text{Equation 9}$$

Pressure inside the Ambu bag is calculated, here P_{in} represent pressure inside Ambu bag, P_{out} represent pressure outside (leaving) the Ambu bag. Similar abbreviation is used in the case of force F_{in}, F_{out}, F_{app}.

Now for determining the pressure inside the Ambu bag, by using ideal gas law. The temperature used in equation is room temperature 25℃=298.15 K,

By Ideal Gas Law,

$$PV = nRT$$

$$P = \frac{nRT}{V}$$

In this case pressure inside,

$$P_{in} = \frac{nRT}{V} \quad \textit{Equation 10}$$

Human respiration is based upon Boyle's law,

$$P_1V_1 = P_2V_2 \quad \textit{Equation 11}$$

4 Medical Device Requirement

4.1 Complications

One more point which cannot be neglected is due to limited control/ set parameters (cheap ventilators) the entire breathing requirement is analyzed by machine; in this case the patient will take mechanical input weather it is required or not. It is a very uncomfortable and this requires the patient to be heavily sedated. This process could result in worsening the barotrauma, if patient's diaphragm and intercostal muscles are resisting the inhalation.

4.2 Product Design specifications

Medical Requirement	User specified multiple breath/min settings
	Multiple tidal volume settings
	Inspiration/ Expiration ratio
	Maximum Pressure limiting
Mechanical	Robust Mechanical and Electrical system
	Minimal Powerd
	Provide Mulitple control settings

Table 1 Design specifications

5 Device Design

5.1 Machine Design

The ventilator consists of two panels, lower panel is fixed and Ambu bag is placed on it. The upper panel is connected with motor on the one side which rotates and on the other side it is connected with hinge mechanism with the lower panel. When rotation takes place the hinge mechanism allows upper panel to move upward and downward, hence the Ambu bag compresses and ventilation takes place.

Figure 1 Side angle view of CEA-PR

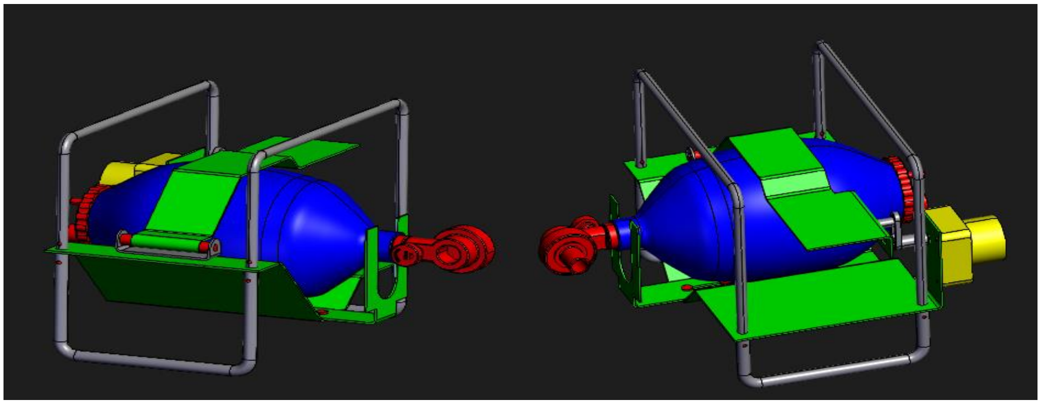
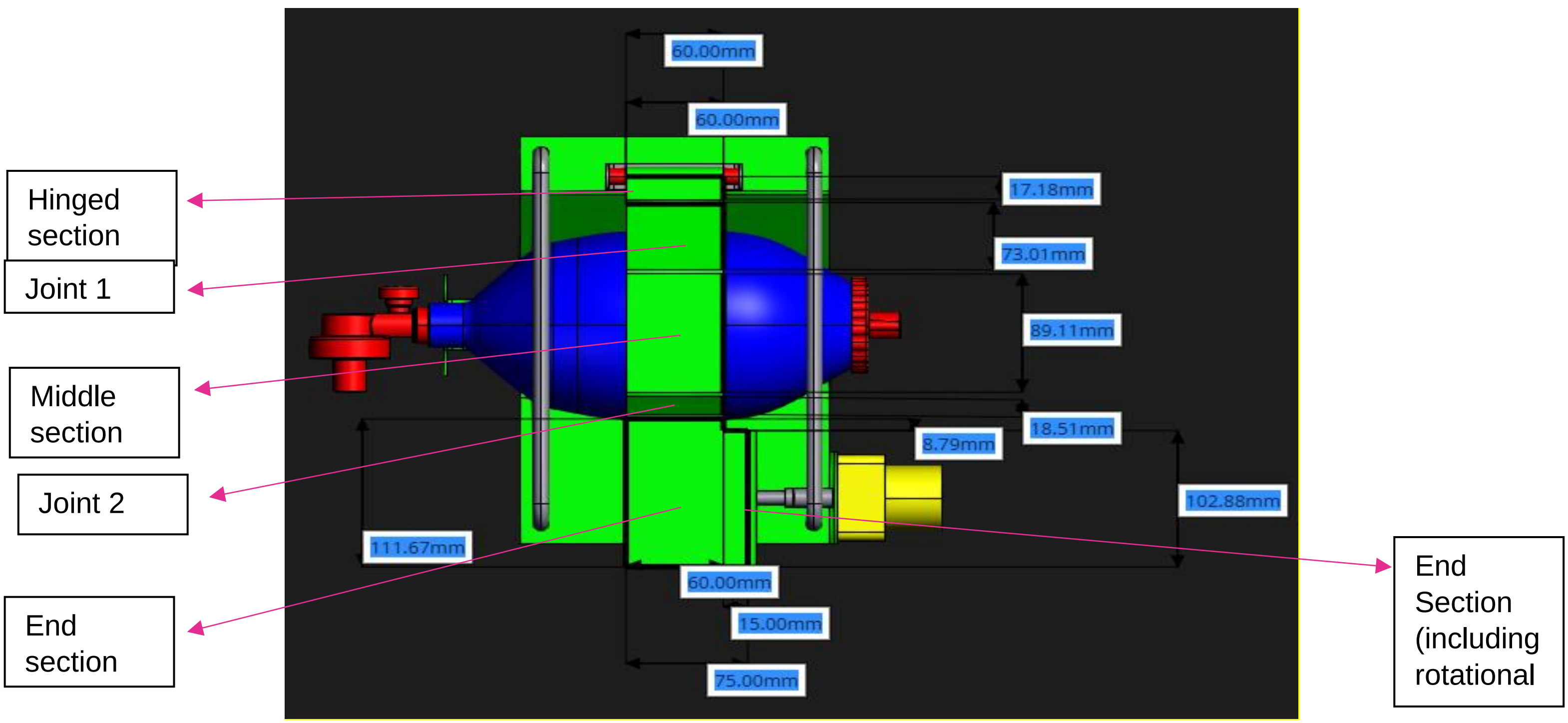


Figure 2 Dimension of upper panel, divided part wise



Dimension of Upper Panel (from hinge side)	Length (mm)	Breadth (mm)
Hinged section	17.18	60
Joint 1	73.01	60
Middle section	89.11	60
Joint 2	18.51	60
End section	111.67	60
End section (including additional patch for rotatinal cavity)	102.88	15

Table 2 Dimension of upper panel

The sections of upper panel is divided on the basis of joint, it has been divided to understand the dimension of middle section which is creating pressure.

Rotational arm which moves the panel upward and downward = 0.031m = radius of rotating circular path.

5.2 Geometry of Ambu Bag

There are two tubing port available on the inlet side, the big port is the reservoir port, small port is for oxygen tubing. On the patient side the expiratory valve is present, for the safety if patient is trying to breath from the other side or putting effort (PEEP valve). Fish mouth valve is present at the patient side, it opens up when the Ambu bag is compressed. For expiration same path is not used, an expiratory duct is present around fish mouth valve. All valves present in the Ambu bag is one-way valves.

Volume of Ambu bag is 1.475 L, according to Ambu website model SPUR II adult resuscitator, with one hand compression releases 800 ml and with two hand compression releases 1100 ml, reservoir volume is 2600 ml and dimension is 295x127 mm.

In this ventilator design Ambu bag can be used with or without oxygen tubing. If patient is critically ill and need 100% of oxygen supply than oxygen tubing can be fitted with reservoir bag. In the case of 100% oxygen delivery if reservoir bag is not attached the open cavity can dilute the oxygen up to 40%, hence the patient will get diluted concentration of oxygen. Whereas using this kit without oxygen supply is also possible as it takes oxygen present in the air.

5.3 Selected motor specification

RS Pro Synchronous is the selected motor, the specification is listed below,

Output Speed	20 rpm
Supply Voltage	230 V
Maximum Output Torque	0.016 Nm
Dimension	60x60x49.5 mm
Gear Ratio	25:01:00

Table 3 Specification of motor

6 Calculations

The calculation here is based on these values,

Weight	75 Kg
Tidal Volume	6 ml
Respiration Rate	12
Temperature	25˚C (298.15 K)
Torque	0.016 Nm
Density	1.225
Radius	0.031 m

Table 4 Values used in calculation

6.1 Pressure inside Ambu Bag

From $P_{in} = \frac{nRT}{V}$ Equation 10

Where,

R = 0.08206, V = 1.475 L (see section description), T = 298.15 K, n (no. of moles) =? ρ =1.225,

no. of moles can be calculated by identifying mass of gas which can identify moles,

so,

$$m = \rho V \quad \text{Equation 12}$$

$$\sqrt[3]{V} = \sqrt[3]{1.475}$$

$$V = 1.3832$$

Putting value $m = \rho V$ Equation 12

$$m = 1.225 * 1.3832 = 1.80688\ gm$$

$$= 0.00180688\ kg$$

Air molecular mass = 28.9647 gm/mol

So, by dividing mass of air = 1.80688 gm by molar mass of air 28.9647 gm/ mol we can get no. of moles,

$$n = \frac{1.80688\ gm}{28.9647\ gm/mol}$$

$$n = 0.0623821\ mol$$

Substituting the values in eq (10),

$$P_{in} = \frac{0.06238 * 0.08206 * 298.15}{1.3832}$$

$$P_{in} = 1.1278\ Pa$$

Is the pressure present inside the Ambu bag is P_{in} known, for compression $P_{app} > P_{in}$.

Rpm can be defined by respiratory rate so,

$if\ one\ round\ per\ second, than\ in\ a\ minute\ =$ 60 rpm,

$by\ using\ normal\ breathing\ rate =$ 12 breaths per minute (5 sec interval)

$= 12\ rpm$

Flow rate calculation,

Substituting values in $Flow\ rate = Tidal\ Volume\ /kg * Respiration\ rate$ Equation 1

Taking least here 6 ml per kg so,

$$= 6\frac{ml}{kg} * 75kg$$

$$= 450\ ml = 0.45\ L$$

$$Flow\ rate = 0.45 * 12 = 5.41\ L/min$$

Tidal Volume 6			
Weight	Tidal Volume	RR	Flow Rate
75	6	12	5.4
75	6	14	6.3
75	6	16	7.2
75	6	18	8.1
75	6	20	9
75	6	22	9.9
75	6	24	10.8

Table 5 Flow rate calculated values

Calculating angular velocity on the basis of rpm by equation (3),

$$\omega = \frac{12}{60\ sec/min} * 2\pi \frac{rad}{rev}$$

$$\omega = 1.256\ rad/sec$$

Linear velocity by $v = \omega * r$ Equation 4,

$$v = 1.256 * 0.031 = 0.038 \frac{m}{s}$$

Calculating Power by $Power\ (P) = Torque(\tau) * AngularVelocity\ (\omega)$ Equation 5

$$P = 1.256 * 0.016 = 0.020096\ W$$

Force applied (F_{app}) can be calculated by $P = F * V$ Equation 8,

$$F_{app} = \frac{0.020096}{0.038} = 0.49\ N$$

For Pressure (P_{app}) by equation (9), value of area is taken from (Table 1) middle section,

$$P_{app} = \frac{0.49}{0.005346} = 91.65731\ Pa$$

Arm Length 0.031 m										
2pi	sec/min	R (m)	Torque (Nm)	RPM	Angular Velocity (rad/sec)	Velocity (m/s)	Power (W)	Force (N)	Area (m^2)	Pressure (Pa)
6.283185307	60	0.031	0.016	12	1.256637061	0.038955749	0.020106193	0.516129	0.005346	96.54489941
6.283185307	60	0.031	0.016	14	1.466076572	0.045448374	0.023457225	0.516129	0.005346	96.54489941
6.283185307	60	0.031	0.016	16	1.675516082	0.051940999	0.026808257	0.516129	0.005346	96.54489941
6.283185307	60	0.031	0.016	18	1.884955592	0.058433623	0.030159289	0.516129	0.005346	96.54489941
6.283185307	60	0.031	0.016	20	2.094395102	0.064926248	0.033510322	0.516129	0.005346	96.54489941

Table 6 Angular velocity, Linear velocity, Power, Applied force and power calculated values.

The pressure value here is applied pressure and force is applied force

7 Specifications

7.1 Machine Control

The primary guidance is to limit the volume and pressure of air entering the lungs. In every action speed of the upper panel of the machine is going to be constant, because more force can lead to more pressure (force is directly proportional to the pressure), which can disturb the flow rate. With constant speed flow rate can be constant. For increase breath/ minute or respiratory rate (RR) interval of the mechanism could be increased. So, Respiration rate can be controlled by rpm, torque value can control applied pressure and force.

In the preliminary research it was found that limiting the compression with the force and pressure was impossible in this kind of mechanism, the compression was the result of rotation. So, in this case it does not matter how much force is applied regardless of the force the arm will rotate and the panel will go downward. It means that the Radius of circular path (R) or the rotating arm controls the compression. For different values of compression (flow rate) the radius of the circular path could decrease (size of the rotating arm could be decreased).

As an Assumption,

$\text{if compression by } 0.031\text{m rotating arm} \approx \text{two hand compression of ambu bag } 1100 \text{ ml}$

that rotating arm size can be assumed by equating, the required flow rate to the upper expression.

So, arm size for a 0.45 L (from the above flow rate calculation),

Let arm size be x,

$$\frac{1.1\,L}{0.45\,L} = \frac{0.031\,m}{x}$$

$$x = 0.0126\,m.$$

By this assumption flow rate can be controlled according to the patient's conditions with multiple possibilities of settings. In this report few rotating arm sizes have been used in calculation and the data has been presented under appendix section. All other required arm sizes can be calculated by using similar approach.

For increase in Tidal volume pressure of the cam can be increased, but speed of the upper panel should be constant, by using pressure compression of the Ambu bag can be controlled which is responsible for tidal volume.

Figure 3 A watch strap, the design of rotating arm based on watch strap allows for multiple setting options

As it can be seen that different tidal volume and weight combinations requires different arm length, in thus case a new design can be introduced based upon watch strap. Where holes can be marked on the scaled positions according to arm length calculation and the little part which moves back and forth on the upper panel. Could be removed and fix (using a nut) to required position.

PDS Requirement	*Controled Via*
User Specified breath/ min	RPM
Tidal volume	Rotational Arm
Maximum Pressure Limiting	Torque
Flow Rate	Rotational Arm
	RPM

Table 7 CEA-PR controls

Tidal Volume 6				
Weight	Tidal Volume	RR	Flow Rate	Arm length (R)
75	6	12	5.4	0.012681818
75	6	14	6.3	0.012681818
75	6	16	7.2	0.012681818
75	6	18	8.1	0.012681818
75	6	20	9	0.012681818
75	6	22	9.9	0.012681818
75	6	24	10.8	0.012681818

Table 8 Arm length according to flow rate

8 Conclusion

The result obtained here are based on the theoretical evaluation. Entire set of result is available in the Appendix section, according to research and calculations the CEA-PR can provide multiple settings of flow rate, tidal volume and pressure control. It can provide aid to an ARDS affected patient which requires low inspiratory pressure and high tidal volume as well as to a patient who requires normal tidal volume and high flow rate. All the data is tabulated according to different weight and different torque values, in which different settings and their outcome which can be achieved by machine is present. The ‘R’ in the table represents radius of the circular path or the rotating arm.

9 References

10 Appendix

Radius of circular path or rotating arm length (R) is measured in m.

10.1 Calculated flow control and Arm length Value (for compression)

10.1.1 Weight 60

Tidal Volume 5				
Weight	Tidal Volume	RR	Flow Rate	Arm length (R)
60	5	12	3.6	0.008454545
60	5	14	4.2	0.008454545
60	5	16	4.8	0.008454545
60	5	18	5.4	0.008454545
60	5	20	6	0.008454545
60	5	22	6.6	0.008454545
60	5	24	7.2	0.008454545

Tidal Volume 6				
Weight	Tidal Volume	RR	Flow Rate	Arm length (R)
60	6	12	4.32	0.010145455
60	6	14	5.04	0.010145455
60	6	16	5.76	0.010145455
60	6	18	6.48	0.010145455
60	6	20	7.2	0.010145455
60	6	22	7.92	0.010145455
60	6	24	8.64	0.010145455

Tidal Volume 7				
Weight	Tidal Volume	RR	Flow Rate	Arm length (R)
60	7	12	5.04	0.011836364
60	7	14	5.88	0.011836364
60	7	16	6.72	0.011836364
60	7	18	7.56	0.011836364
60	7	20	8.4	0.011836364
60	7	22	9.24	0.011836364
60	7	24	10.08	0.011836364

Tidal Volume 8				
Weight	Tidal Volume	RR	Flow Rate	Arm length (R)
60	8	12	5.76	0.013527273
60	8	14	6.72	0.013527273
60	8	16	7.68	0.013527273
60	8	18	8.64	0.013527273
60	8	20	9.6	0.013527273
60	8	22	10.56	0.013527273
60	8	24	11.52	0.013527273

10.1.2 Weight 70

Tidal Volume 5				
Weight	Tidal Volume	RR	Flow Rate	Arm length (R)
70	5	12	4.2	0.009863636
70	5	14	4.9	0.009863636
70	5	16	5.6	0.009863636
70	5	18	6.3	0.009863636
70	5	20	7	0.009863636
70	5	22	7.7	0.009863636
70	5	24	8.4	0.009863636

Tidal Volume 6				
Weight	Tidal Volume	RR	Flow Rate	Arm length (R)
70	6	12	5.04	0.011836364
70	6	14	5.88	0.011836364
70	6	16	6.72	0.011836364
70	6	18	7.56	0.011836364
70	6	20	8.4	0.011836364
70	6	22	9.24	0.011836364
70	6	24	10.08	0.011836364

Tidal Volume 7				
Weight	Tidal Volume	RR	Flow rate	Arm length (R)
70	7	12	5.88	0.013809091
70	7	14	6.86	0.013809091
70	7	16	7.84	0.013809091
70	7	18	8.82	0.013809091
70	7	20	9.8	0.013809091
70	7	22	10.78	0.013809091
70	7	24	11.76	0.013809091

Tidal Volume 8				
Weight	Tidal Volume	RR	Flow Rate	Arm length (R)
70	8	12	6.72	0.015781818
70	8	14	7.84	0.015781818
70	8	16	8.96	0.015781818
70	8	18	10.08	0.015781818
70	8	20	11.2	0.015781818
70	8	22	12.32	0.015781818
70	8	24	13.44	0.015781818

10.1.3 Weight 75

Tidal Volume 5				
Weight	Tidal Volume	RR	Flow Rate	Arm length (R)
75	5	12	4.5	0.010568182
75	5	14	5.25	0.010568182
75	5	16	6	0.010568182
75	5	18	6.75	0.010568182
75	5	20	7.5	0.010568182
75	5	22	8.25	0.010568182
75	5	24	9	0.010568182

Tidal Volume 6				
Weight	Tidal Volume	RR	Flow Rate	Arm length (R)
75	6	12	5.4	0.012681818
75	6	14	6.3	0.012681818
75	6	16	7.2	0.012681818
75	6	18	8.1	0.012681818
75	6	20	9	0.012681818
75	6	22	9.9	0.012681818
75	6	24	10.8	0.012681818

Tidal Volume 7				
Weight	Tidal Volume	RR	Flow rate	Arm length (R)
75	7	12	6.3	0.014795455
75	7	14	7.35	0.014795455
75	7	16	8.4	0.014795455
75	7	18	9.45	0.014795455
75	7	20	10.5	0.014795455
75	7	22	11.55	0.014795455
75	7	24	12.6	0.014795455

Tidal Volume 8				
Weight	Tidal volume	RR	Flow Rate	Arm length (R)
75	8	12	7.2	0.016909091
75	8	14	8.4	0.016909091
75	8	16	9.6	0.016909091
75	8	18	10.8	0.016909091
75	8	20	12	0.016909091
75	8	22	13.2	0.016909091
75	8	24	14.4	0.016909091

10.1.4 Weight 80

Tidal Volume 5				
Weight	Tidal Volume	RR	Flow Rate	Arm length (R)
80	5	12	4.8	0.011272727
80	5	14	5.6	0.011272727
80	5	16	6.4	0.011272727
80	5	18	7.2	0.011272727
80	5	20	8	0.011272727
80	5	22	8.8	0.011272727
80	5	24	9.6	0.011272727

Tidal Volume 6				
Weight	Tidal Volume	RR	Flow Rate	Arm length (R)
80	6	12	5.76	0.013527273
80	6	14	6.72	0.013527273
80	6	16	7.68	0.013527273
80	6	18	8.64	0.013527273
80	6	20	9.6	0.013527273
80	6	22	10.56	0.013527273
80	6	24	11.52	0.013527273

Tidal Volume 7				
Weight	Tidal Volume	RR	Flow Rate	Arm length (R)
80	7	12	6.72	0.015781818
80	7	14	7.84	0.015781818
80	7	16	8.96	0.015781818
80	7	18	10.08	0.015781818
80	7	20	11.2	0.015781818
80	7	22	12.32	0.015781818
80	7	24	13.44	0.015781818

Tidal Volume 8				
Weight	Tidal Volume	RR	Flow Rate	Arm length (R)
80	8	12	7.68	0.018036364
80	8	14	8.96	0.018036364
80	8	16	10.24	0.018036364
80	8	18	11.52	0.018036364
80	8	20	12.8	0.018036364
80	8	22	14.08	0.018036364
80	8	24	15.36	0.018036364

10.1.5 Weight 90

Tidal Volume 5				
Weight	Tidal Volume	RR	Flow Rate	Arm length (R)
90	5	12	5.4	0.012681818
90	5	14	6.3	0.012681818
90	5	16	7.2	0.012681818
90	5	18	8.1	0.012681818
90	5	20	9	0.012681818
90	5	22	9.9	0.012681818
90	5	24	10.8	0.012681818

Tidal Volume 6				
Weight	Tidal Volume	RR	Flow Rate	Arm length (R)
90	6	12	6.48	0.015218182
90	6	14	7.56	0.015218182
90	6	16	8.64	0.015218182
90	6	18	9.72	0.015218182
90	6	20	10.8	0.015218182
90	6	22	11.88	0.015218182
90	6	24	12.96	0.015218182

Tidal Volume 7				
Weight	Tidal Volume	RR	Flow rate	Arm length (R)
90	7	12	7.56	0.017754545
90	7	14	8.82	0.017754545
90	7	16	10.08	0.017754545
90	7	18	11.34	0.017754545
90	7	20	12.6	0.017754545
90	7	22	13.86	0.017754545
90	7	24	15.12	0.017754545

Tidal Volume 8				
Weight	Tidal volume	RR	Flow Rate	Arm length (R)
90	8	12	8.64	0.020290909
90	8	14	10.08	0.020290909
90	8	16	11.52	0.020290909
90	8	18	12.96	0.020290909
90	8	20	14.4	0.020290909
90	8	22	15.84	0.020290909
90	8	24	17.28	0.020290909

10.2 Calculated values on the basis of different torque and Arm length values (for Pressure and Force control)

10.2.1 Torque 0.01

The area mentioned in the table is upper panel Table 2 (middle section) area, Force is applied force and pressure is applied pressure.

Arm Length 0.015 m										
2pi	sec/min	R (m)	Torque (Nm)	RPM	Angular Velocity (rad/sec)	Velocity (m/s)	Power (W)	Force (N)	Area (m^2)	Pressure (Pa)
6.283185	60	0.015	0.01	12	1.256637061	0.018849556	0.012566371	0.666666667	0.005346	124.7038284
6.283185	60	0.015	0.01	14	1.466076572	0.021991149	0.014660766	0.666666667	0.005346	124.7038284
6.283185	60	0.015	0.01	16	1.675516082	0.025132741	0.016755161	0.666666667	0.005346	124.7038284
6.283185	60	0.015	0.01	18	1.884955592	0.028274334	0.018849556	0.666666667	0.005346	124.7038284
6.283185	60	0.015	0.01	20	2.094395102	0.031415927	0.020943951	0.666666667	0.005346	124.7038284
Arm Length 0.02 m										
2pi	sec/min	R (m)	Torque (Nm)	RPM	Angular Velocity (rad/sec)	Velocity (m/s)	Power (W)	Force (N)	Area (m^2)	Pressure (Pa)
6.283185	60	0.02	0.01	12	1.256637061	0.025132741	0.012566371	0.5	0.005346	93.52787131
6.283185	60	0.02	0.01	14	1.466076572	0.029321531	0.014660766	0.5	0.005346	93.52787131
6.283185	60	0.02	0.01	16	1.675516082	0.033510322	0.016755161	0.5	0.005346	93.52787131
6.283185	60	0.02	0.01	18	1.884955592	0.037699112	0.018849556	0.5	0.005346	93.52787131
6.283185	60	0.02	0.01	20	2.094395102	0.041887902	0.020943951	0.5	0.005346	93.52787131
Arm Length 0.031 m										
2pi	sec/min	R (m)	Torque (Nm)	RPM	Angular Velocity (rad/sec)	Velocity (m/s)	Power (W)	Force (N)	Area (m^2)	Pressure (Pa)
6.283185	60	0.031	0.01	12	1.256637061	0.038955749	0.012566371	0.322580645	0.005346	60.34056213
6.283185	60	0.031	0.01	14	1.466076572	0.045448374	0.014660766	0.322580645	0.005346	60.34056213
6.283185	60	0.031	0.01	16	1.675516082	0.051940999	0.016755161	0.322580645	0.005346	60.34056213
6.283185	60	0.031	0.01	18	1.884955592	0.058433623	0.018849556	0.322580645	0.005346	60.34056213
6.283185	60	0.031	0.01	20	2.094395102	0.064926248	0.020943951	0.322580645	0.005346	60.34056213

10.2.2 Torque 0.012

Arm Length 0.015 m										
2pi	sec/min	R (m)	Torque (Nm)	RPM	Angular Velocity (rad/sec)	Velocity (m/s)	Power (W)	Force (N)	Area (m^2)	Pressure (Pa)
6.283185	60	0.015	0.012	12	1.256637061	0.018849556	0.015079645	0.8	0.005346	149.6445941
6.283185	60	0.015	0.012	14	1.466076572	0.021991149	0.017592919	0.8	0.005346	149.6445941
6.283185	60	0.015	0.012	16	1.675516082	0.025132741	0.020106193	0.8	0.005346	149.6445941
6.283185	60	0.015	0.012	18	1.884955592	0.028274334	0.022619467	0.8	0.005346	149.6445941
6.283185	60	0.015	0.012	20	2.094395102	0.031415927	0.025132741	0.8	0.005346	149.6445941

Arm Length 0.02 m										
2pi	sec/min	R (m)	Torque (Nm)	RPM	Angular Velocity (rad/sec)	Velocity (m/s)	Power (W)	Force (N)	Area (m^2)	Pressure (Pa)
6.283185	60	0.02	0.012	12	1.256637061	0.025132741	0.015079645	0.6	0.005346	112.2334456
6.283185	60	0.02	0.012	14	1.466076572	0.029321531	0.017592919	0.6	0.005346	112.2334456
6.283185	60	0.02	0.012	16	1.675516082	0.033510322	0.020106193	0.6	0.005346	112.2334456
6.283185	60	0.02	0.012	18	1.884955592	0.037699112	0.022619467	0.6	0.005346	112.2334456
6.283185	60	0.02	0.012	20	2.094395102	0.041887902	0.025132741	0.6	0.005346	112.2334456

Arm Length 0.031 m										
2pi	sec/min	R (m)	Torque (Nm)	RPM	Angular Velocity (rad/sec)	Velocity (m/s)	Power (W)	Force (N)	Area (m^2)	Pressure (Pa)
6.283185	60	0.031	0.012	12	1.256637061	0.038955749	0.015079645	0.387097	0.005346	72.40867456
6.283185	60	0.031	0.012	14	1.466076572	0.045448374	0.017592919	0.387097	0.005346	72.40867456
6.283185	60	0.031	0.012	16	1.675516082	0.051940999	0.020106193	0.387097	0.005346	72.40867456
6.283185	60	0.031	0.012	18	1.884955592	0.058433623	0.022619467	0.387097	0.005346	72.40867456
6.283185	60	0.031	0.012	20	2.094395102	0.064926248	0.025132741	0.387097	0.005346	72.40867456

10.2.3 Torque 0.014

Arm Length 0.015 m										
2pi	sec/min	R (m)	Torque (Nm)	RPM	Angular Velocity (rad/sec)	Velocity (m/s)	Power (W)	Force (N)	Area (m^2)	Pressure (Pa)
6.283185	60	0.015	0.014	12	1.256637061	0.018849556	0.017592919	0.933333	0.005346	174.5853598
6.283185	60	0.015	0.014	14	1.466076572	0.021991149	0.020525072	0.933333	0.005346	174.5853598
6.283185	60	0.015	0.014	16	1.675516082	0.025132741	0.023457225	0.933333	0.005346	174.5853598
6.283185	60	0.015	0.014	18	1.884955592	0.028274334	0.026389378	0.933333	0.005346	174.5853598
6.283185	60	0.015	0.014	20	2.094395102	0.031415927	0.029321531	0.933333	0.005346	174.5853598

Arm Length 0.02 m										
2pi	sec/min	R (m)	Torque (Nm)	RPM	Angular Velocity (rad/sec)	Velocity (m/s)	Power (W)	Force (N)	Area (m^2)	Pressure (Pa)
6.283185	60	0.02	0.014	12	1.256637061	0.025132741	0.017592919	0.7	0.005346	130.9390198
6.283185	60	0.02	0.014	14	1.466076572	0.029321531	0.020525072	0.7	0.005346	130.9390198
6.283185	60	0.02	0.014	16	1.675516082	0.033510322	0.023457225	0.7	0.005346	130.9390198
6.283185	60	0.02	0.014	18	1.884955592	0.037699112	0.026389378	0.7	0.005346	130.9390198
6.283185	60	0.02	0.014	20	2.094395102	0.041887902	0.029321531	0.7	0.005346	130.9390198

Arm Length 0.031 m										
2pi	sec/min	R (m)	Torque (Nm)	RPM	Angular Velocity (rad/sec)	Velocity (m/s)	Power (W)	Force (N)	Area (m^2)	Pressure (Pa)
6.283185	60	0.031	0.014	12	1.256637061	0.038955749	0.017592919	0.451613	0.005346	84.47678699
6.283185	60	0.031	0.014	14	1.466076572	0.045448374	0.020525072	0.451613	0.005346	84.47678699
6.283185	60	0.031	0.014	16	1.675516082	0.051940999	0.023457225	0.451613	0.005346	84.47678699
6.283185	60	0.031	0.014	18	1.884955592	0.058433623	0.026389378	0.451613	0.005346	84.47678699
6.283185	60	0.031	0.014	20	2.094395102	0.064926248	0.029321531	0.451613	0.005346	84.47678699

10.2.4 Torque 0.016

Arm Length 0.015 m										
2pi	sec/min	R (m)	Torque (Nm)	RPM	Angular Velocity (rad/sec)	Velocity (m/s)	Power (W)	Force (N)	Area (m^2)	Pressure (Pa)
6.283185307	60	0.015	0.016	12	1.256637061	0.018849556	0.020106193	1.066667	0.005346	199.5261255
6.283185307	60	0.015	0.016	14	1.466076572	0.021991149	0.023457225	1.066667	0.005346	199.5261255
6.283185307	60	0.015	0.016	16	1.675516082	0.025132741	0.026808257	1.066667	0.005346	199.5261255
6.283185307	60	0.015	0.016	18	1.884955592	0.028274334	0.030159289	1.066667	0.005346	199.5261255
6.283185307	60	0.015	0.016	20	2.094395102	0.031415927	0.033510322	1.066667	0.005346	199.5261255
Arm Length 0.02 m										
2pi	sec/min	R (m)	Torque (Nm)	RPM	Angular Velocity (rad/sec)	Velocity (m/s)	Power (W)	Force (N)	Area (m^2)	Pressure (Pa)
6.283185307	60	0.02	0.016	12	1.256637061	0.025132741	0.020106193	0.8	0.005346	149.6445941
6.283185307	60	0.02	0.016	14	1.466076572	0.029321531	0.023457225	0.8	0.005346	149.6445941
6.283185307	60	0.02	0.016	16	1.675516082	0.033510322	0.026808257	0.8	0.005346	149.6445941
6.283185307	60	0.02	0.016	18	1.884955592	0.037699112	0.030159289	0.8	0.005346	149.6445941
6.283185307	60	0.02	0.016	20	2.094395102	0.041887902	0.033510322	0.8	0.005346	149.6445941
Arm Length 0.031 m										
2pi	sec/min	R (m)	Torque (Nm)	RPM	Angular Velocity (rad/sec)	Velocity (m/s)	Power (W)	Force (N)	Area (m^2)	Pressure (Pa)
6.283185307	60	0.031	0.016	12	1.256637061	0.038955749	0.020106193	0.516129	0.005346	96.54489941
6.283185307	60	0.031	0.016	14	1.466076572	0.045448374	0.023457225	0.516129	0.005346	96.54489941
6.283185307	60	0.031	0.016	16	1.675516082	0.051940999	0.026808257	0.516129	0.005346	96.54489941
6.283185307	60	0.031	0.016	18	1.884955592	0.058433623	0.030159289	0.516129	0.005346	96.54489941
6.283185307	60	0.031	0.016	20	2.094395102	0.064926248	0.033510322	0.516129	0.005346	96.54489941