



WPI

The Research and Development of
an Equine Endotracheal Y-Piece
Positive End-Expiratory Pressure (EETYPEEP) Valve

A Major Qualifying Project Report submitted to the faculty of

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the degree of Bachelor of Science

Submitted by

A handwritten signature in black ink that reads "Alli Butler".

Alli Butler, RVT

Department of Biomedical Engineering

May 6, 2021

Keywords:

*Positive-end expiratory pressure,
PEEP, equine anesthesia,
atelectasis*

Raymond. L. Page, PhD

Department of Biomedical Engineering,

Worcester Polytechnic Institute

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AUTHORSHIP PAGE

I, Alli Butler, am the sole author of the content of this report.

ACKNOWLEDGEMENTS

I would like to thank the multitude of people who helped with this project and supported me in my endeavor to complete my MQP without a traditional team. First and foremost is Dr. Pen-Ting (Ben) Liao, without whom the very concept of the EETYPEEP would not exist. Ben – thank you for your patience, guidance, and wealth of anesthesia-related knowledge. Next, I would like to thank my work family at Tufts. Over the past almost four years, I have come to love the people I work with and I would never have been able to complete this degree without their love and support. Specifically, I would like to thank the magnificent Matthew Dann for all of his help with the equine mechanical ventilator and developing the methods to test and calibrate the EETYPEEP. I would like to thank Dr. Brian Savilonis for his enthusiasm about this MQP and his help with the calculations for the compression spring. This MQP would have undoubtedly been better if I had taken his Biofluids class before this D-term! Last, but certainly not least, I would like to thank Professor Ray Page for being my advisor and his patience and tutelage with this unconventional MQP.

ABSTRACT

Compression atelectasis is a universal problem in recumbent anesthetized horses due to the weight of the abdominal contents against the diaphragm as well as the positioning of the legs when the animal is hoisted onto the surgical table. Reduced oxygenation occurs because the collapsed alveoli cannot participate in gas exchange, resulting in ventilation-perfusion mismatch. There are no widely accepted methods or devices to prevent these adverse events in equine medicine, although various mechanical ventilation techniques (e.g. alveolar recruitment maneuvers) are employed when hypoxia is evident during anesthesia. Unfortunately, these methods often have unpredictable and deleterious cardiovascular effects and can cause barotrauma to the lung tissue.

Positive end-expiratory pressure (PEEP), defined as the application of positive pressure at the end of expiration to maintain functional residual capacity, has been long identified as an effective means to prevent alveolar collapse and improve gas exchange. This MQP is the beginning of the development of a novel PEEP device for horses for the prevention of atelectasis to be used while the animal is being hoisted. This MQP report outlines this process and result, as well as the hopes for the future of this project.

EXECUTIVE SUMMARY

I. INTRODUCTION

During any surgical or diagnostic procedure that requires the equine patient to be recumbent for an extended period of time, general anesthesia is usually required. Unfortunately, standard anesthetic protocols put the horse at risk for serious complications associated with their size and peculiar respiratory physiology. Specifically, after a horse is initially sedated with intravenous drugs in a padded stall, it must be transported to the surgical suite by being hoisted up by its legs using hobbles attached to a hydraulic lift (see Fig 1, page 9). This puts the horse at great risk of atelectasis (also known as collapsed lung) because the weight of the abdominal organs presses against the diaphragm. This, in combination with the depressive effects of the anesthetic drugs and the position of the horse's legs against the ribcage while being hoisted, compromises their ability to breathe fully, leading to low levels of oxygen in the blood.

Compression atelectasis and its associated complications have also been observed during anesthesia in obese human patients. Anesthesiologists and bariatric physicians now recommend the application of positive airway pressure before induction and after intubation as method for preventing atelectasis. Similar strategies could potentially be applied in horses. This MQP is the beginning of the development of such strategies.

II. DESIGN PROCESS

A. Study of PEEP Valve Design in Human Medicine

The most common method to prevent atelectasis is the use of positive end-expiratory pressure, also known as PEEP. The principle behind this method is simple: maintain a prescribed level of positive pressure at the end of a breath to keep the alveoli open. The level of positive pressure typically ranges between 5 and 30cmH₂O, depending on several patient-specific factors (e.g., lung compliance). The typical adjustable PEEP valve has three main components: a diaphragm that covers the outlet, a spring attached to the diaphragm, and a screw cap that, when tightened, compresses the spring to create the pressure against the diaphragm. When the patient exhales, the valve opens if the pressure exceeds the PEEP setting.

B. PEEP Valve Components and Dimensions

To provide PEEP to an equine patient before it reaches the ventilator in the surgical suite requires a device that can be easily attached and removed from the endotracheal (ET) tube. Connecting directly to ET tube would also require unrestricted inspiratory flow. To meet these requirements, the main body of the device was designed as a Y-piece with one-way inspiratory and expiratory arms. Using a standard adjustable PEEP valve as a model, the components were designed using SolidWorks and produced using Ultimaker 3D printers in the Foise Prototyping Lab. The compression spring with a spring rate of 0.182N/mm was used to provide 5cmH₂O pressure to the outlet for every 5mm of compression. After several failed attempts to create a one-way inspiratory valve that would remain air-tight during expiration, a final design incorporated a cross-slit duckbill valve (from minivalve.com).

III. FINAL DESIGN AND CALIBRATION

The initial testing was attempted using a large animal ventilator at the Tufts University Cummings School of Veterinary Medicine. Unfortunately, the built-in safety mechanisms made this impossible. Therefore, in an attempt to create the PEEP settings, a testing apparatus was constructed as follows. The equine endotracheal Y-piece positive end-expiratory pressure (EETYPEEP) valve was connected to the ET tube, which was placed within a transparent tube to maintain stability and then connected to the testing apparatus. To model the tidal volume, the opposite end was constructed with two breathing bags, each with a capacity of 3 liters. The entire apparatus was sealed with a rubberized coating to prevent leaks. Next, the breathing bags were inflated using an air pump and the system was closed to maintain the pressure. Beginning with the EETYPEEP closed, the pressure was monitored on a digital manometer as the cap was loosened. Ideally, the level of the cap would have been marked to define the PEEP setting in 5cmH₂O increments. However, due to vibrations in the air pump and other factors, the results were not consistent.

IV. CONCLUSION

The objective of this MQP was to design a novel bi-directional PEEP valve that could be connected to an equine endotracheal tube to prevent or decrease atelectasis in horses when they are hoisted into the surgical suite. This was achieved using standard PEEP valves as a model,

adapted for equine proportions and integrating a one-way inspiratory arm. The ETTYPEEP concept had never been considered before this MQP, and many aspects have yet to be fully developed. There were many limitations that can be improved in future work. Namely, the design of the inspiratory inlet was limited by the materials available (a free sample valve that was too small for the design specifications) and the imprecise testing apparatus and method. It is my hope that future MQP teams will be inspired by my work to further investigate and improve the ETTYPEEP device that could one day be used to help horses around the world.

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List of Abbreviations

ARM, RM: alveolar recruitment maneuver

ARMM: anesthesia-related morbidity and mortality

CMV: controlled mechanical ventilation

FiO₂: fraction of inspired oxygen

I:E Ratio: inspiratory-expiratory ratio

PaO₂: partial pressure of oxygen in arterial blood (mmHg)

PEEP: positive end-expiratory pressure

PIP: positive inspiratory pressure

SpO₂: oxygen saturation in the blood (%)

VILI: ventilator-induced lung injury

V/Q Mismatch: ventilation-perfusion mismatch

CHAPTER 1 – INTRODUCTION

The biomedical challenges of veterinary medicine are limitless, primarily due to the multitude of species and each species' unique anatomy. Equine medicine is no exception. During any surgical or diagnostic procedure that requires the patient to be recumbent for an extended period of time, general anesthesia is usually required. Unfortunately, standard anesthetic protocols put the patient at risk for serious complications associated with their size and peculiar respiratory physiology.

Specifically, after a horse is initially sedated with intravenous drugs in a padded stall, it must be transported to the surgical suite by being hoisted up by its legs using hobbles attached to a hydraulic lift (Fig. 1). This puts the horse at great risk of *atelectasis* (also known as collapsed lung) because the weight of the abdominal organs presses against the diaphragm. This, in combination with the depressive effects of the pre-anesthetic drugs and the position of the horse's legs against the ribcage while being hoisted, has significant effects on his or her breathing, leading to low levels of oxygen in the blood.



Figure 1: An anesthetized horse being hoisted into the surgical suite at the Veliefendi Equine Hospital in Istanbul (2015).

Adapted from [1]

Insufficient oxygen in the blood (*hypoxemia*) can lead to tissue death and brain injury if not corrected promptly. As such, horses are immediately connected to an anesthesia machine or

mechanical ventilator (via an endotracheal tube) as soon as they are settled into position to provide supplemental oxygen. While increasing the percent of inspired oxygen (%FiO₂) can correct hypoxemia, it cannot “reinflate” collapsed alveoli.

When the patient is connected to a mechanical ventilator, certain measures can be taken to attempt to reinflate the lungs. The anesthetist may perform an *alveolar recruitment maneuver* (ARM), which can increase the amount of air in the lungs by providing a controlled breath at a prescribed level of pressure. Unfortunately, studies have shown that this can result in deleterious effects on the cardiovascular system, due to the increase in pressure on the heart and blood vessels.

Hoisting-induced compression atelectasis has been treated as an unavoidable problem in equine anesthesia for decades. However, other types of atelectasis have been prevented using positive end-expiratory pressure (PEEP) in human and veterinary medicine for even longer. The objectives of this MQP are (1) examination the current methods of providing PEEP in humans and horses; (2) use the fluid mechanics principles of current PEEP valve models to design a device to prevent atelectasis in horses; (3) create a prototype of the device and calibrate it using volumes that model equine tidal volumes.

After thoroughly reviewing literature on the subjects of equine anesthesia, mechanical ventilation, respiratory anatomy and physiology, and studies on atelectasis and its associated complications and treatments, I spoke with the Dr. PenTing (Ben) Liao (the originator of the idea for this MQP and a board-certified veterinary criticalist and anesthesiologist). He provided the design requirements and specific details regarding anesthetic equipment. Prototypes were designed using SolidWorks (Dassault Systèmes, 2019) and printed using Ultimaker 3D printers in the Foise Prototyping Lab.

With the help of Dr. Brian Savilonis, I calculated the spring rate required for the compression spring used within the PEEP valve. Several options were purchased for testing from TheSpringStore.com (Access Spring, Colton, CA). With the help of Matthew Dann (a board-certified veterinary anesthesia technician) at the Tufts University Cummings School for Veterinary Medicine, I used a large animal mechanical ventilator to test the device and calibrate the settings.

The following chapters outline this process, beginning with the literature review focusing on equine respiratory mechanics and the current methods of treating atelectasis in horses. Because no

preventative methods have been established in horses, I looked to those methods used in human medicine, specifically bariatric anesthesia. This will be followed by the project strategy (including objectives and device constraints), the design process and device iterations, design validation and verification, and lastly discussion and conclusion with recommendations for further work.

CHAPTER 2: LITERATURE REVIEW

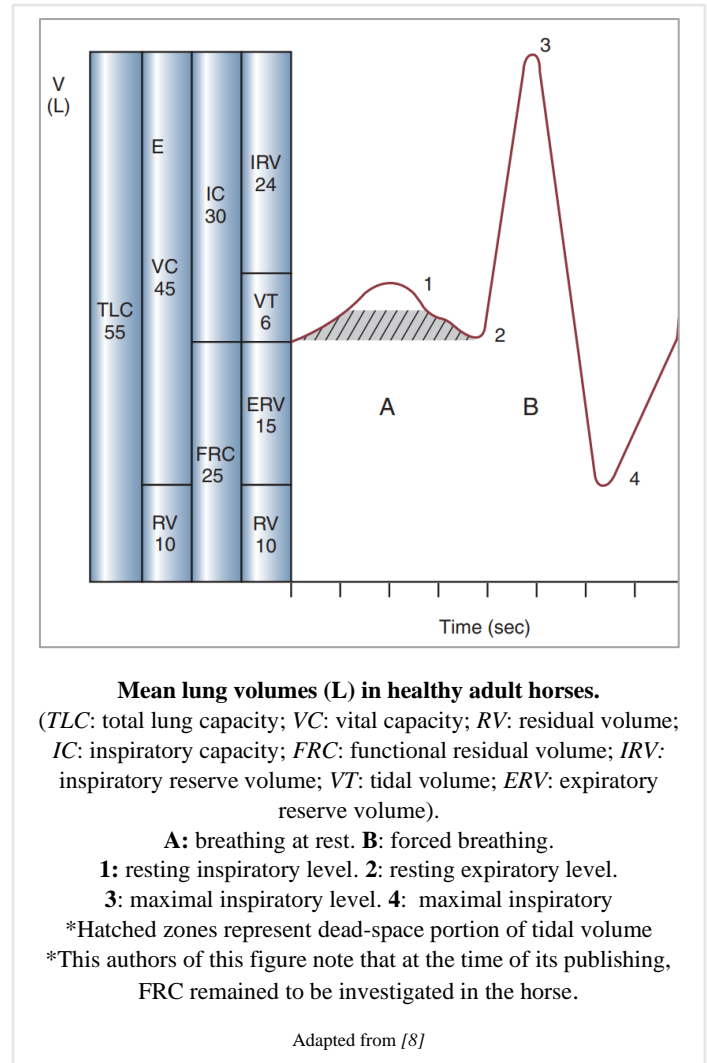
It is widely accepted that the practice of veterinary medicine began with the care of domesticated animals used for food and labor. In his 1939 *History of Veterinary Medicine*, Dr. Earl Guthrie explained that the Latin verb *veheri* (“to draw” or “pull”) likely gave rise to the term veterinarian to describe someone who cares for beasts of burden in ancient practice. The domestic horse (*Equus caballus*) has been a crucial part of human culture for millennia, used for transportation, agricultural development, military operations, sport, and companionship. According to data compiled by the Food and Agriculture Organization of the United Nations, there were nearly 60 million horses worldwide in 2018, with over 10 million in the United States alone.² According to the American Horse Council Foundations’ 2017 National Economic Impact Study, “the horse industry contributes approximately \$50 billion in direct economic impact to the U.S. economy, and has a direct employment impact of 988,394 jobs.”³

Horses are an undeniably significant part of human history and culture. However, much is still poorly understood about their anatomy and physiology and how to best treat their illnesses. As such, it is important to better our understanding of particular risk factors to ensure that the medical care we provide them does not inadvertently cause harm.

Equine respiratory anatomy and physiology

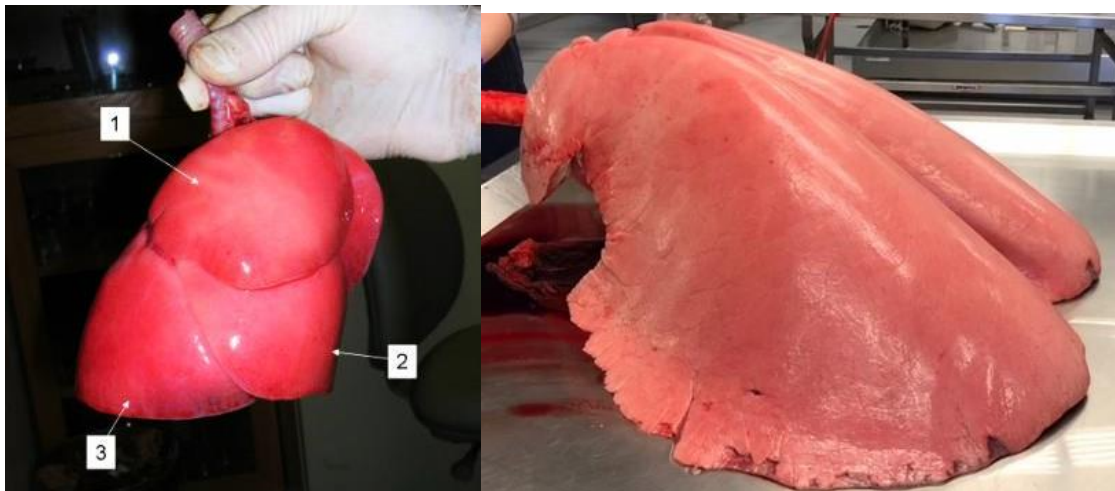
The mechanical physiology of respiration is dependent upon relative pressures within the thorax and the volume of air in the lungs. The total lung capacity (TLC), which is approximately 55L on average in the horse, can be divided in the various volumes based on their function in the respiratory cycle (See Fig. 2).

Tidal volume is defined as the volume of air inhaled or exhaled during one normal breath.⁴ Under



normal physiological conditions, the tidal volume in a healthy horse at rest is approximately 10 to 15 milliliters per kilogram, or an average of 5.6 liters. However, only 40-50% of tidal volume is alveolar, while the remaining 50-60% is physiological dead space (the upper airways, trachea, bronchi, and bronchioles) that does not participate in gas exchange (see hatched zones in Fig. 2).⁵ In contrast, the anatomical dead space in the human respiratory system is approximately 30%.⁶

The gross anatomy of horse lungs is also unique. Unlike most mammals, a horse's lungs are not divided into discrete lobes (see Fig. 3). Instead, the lung parenchyma is separated by elastic collagenous septa. This limits collateral ventilation (i.e. ventilation across lung tissue through non-bronchial pathways). In fact, the ventilation of different pulmonary regions is more synchronized due to the mechanical interaction and interdependence of the adjacent lung fields.⁷



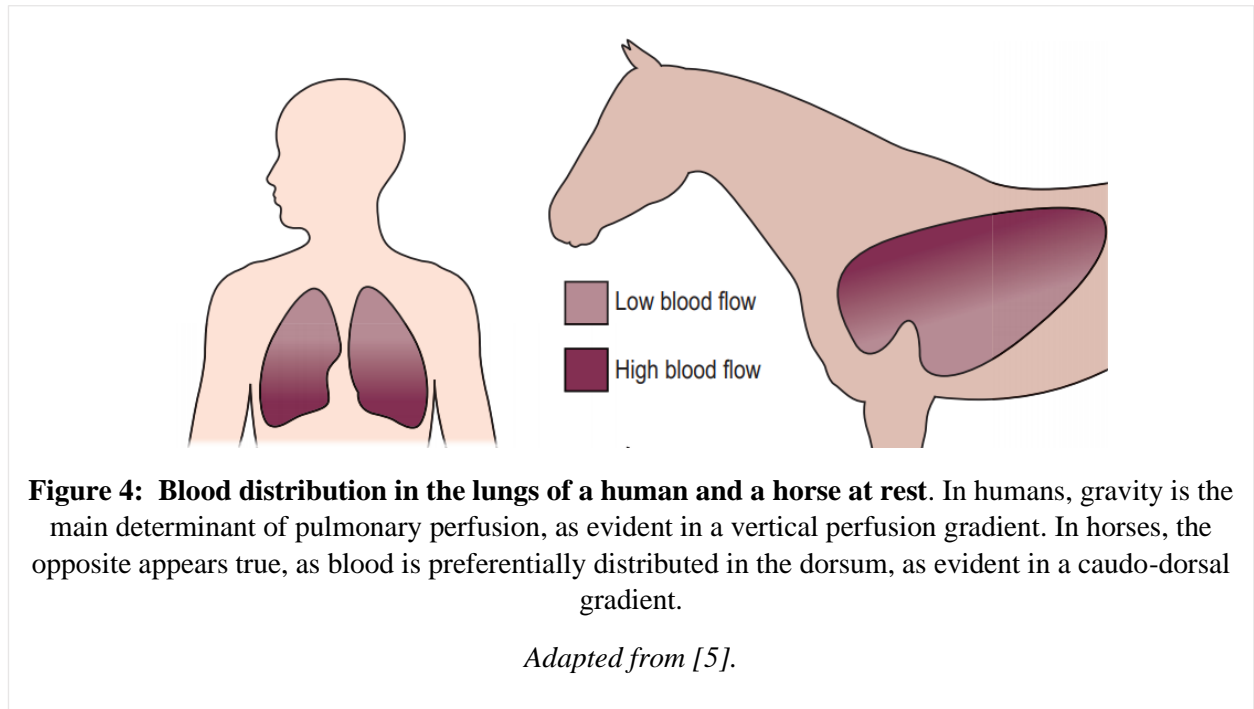
Inflated lungs of a racoon (left) and a horse (right). The right cranial, medial, and caudal lobes of the racoon lung are labeled (1, 2, and 3, respectively). Equine lungs lack such discrete separations.

Sources: https://campus.murraystate.edu/faculty/tderting/cva_atlases/raccoon_respiratory/lungs_inflated_right.htm

<https://flairstrips.com/blog/horse-lungs-vs-human-lungs-learn-about-horse-lung-health/>

As gas exchange occurs between alveoli and their surrounding capillary network, it is necessary to examine equine pulmonary vasculature and blood flow distribution. Although the phenomenon is still not fully understood, studies using fluorescent microspheres have shown that blood distribution is much more condensed in the dorsal lung fields.⁸ In other words, the pulmonary vasculature is not gravity-dependent as one might expect. (see Fig. 4).⁹ To make matters more complicated, ventilation is also unevenly distributed in the lungs, primarily due to nonuniform

intrapleural pressure changes within the thorax and disparities in compliance and resistance in the small airways.⁷



Physiology follows close behind such bizarre anatomy. Most notable is the unique equine breathing strategy. Horses have biphasic respiration with initial active and subsequent passive components during inspiration and expiration. Like humans, the initial stage of expiration is passive, but it is completed with the aid of abdominal muscle activity resulting in deflation below relaxed volume.¹⁰ This results in mechanical equilibrium of the respiratory system at the midpoint of tidal volume instead of the point of functional residual capacity (FRC), as seen in other species.¹¹ By its nature, FRC cannot be measured directly and is a calculated value. Under normal conditions, FRC is estimated to be approximately 20L in the average horse. It maintains airway patency, allowing gas exchange to continue between each breath. However, FRC remains to be fully investigated in the horse and may in fact not be the most suitable termⁱ.

ⁱ FRC is defined as “the total amount of air in a person’s lungs at the lowest point in their tidal volume” and the point at which “the inner recoil forces of the lung due to the elastic tissue of the alveoli, and [the forces of] the chest wall which wants to expand outwards” are in equilibrium (Hopkins & Sharma, 2021). Based on this definition, it is often said that horse “breathe around” their FRC.

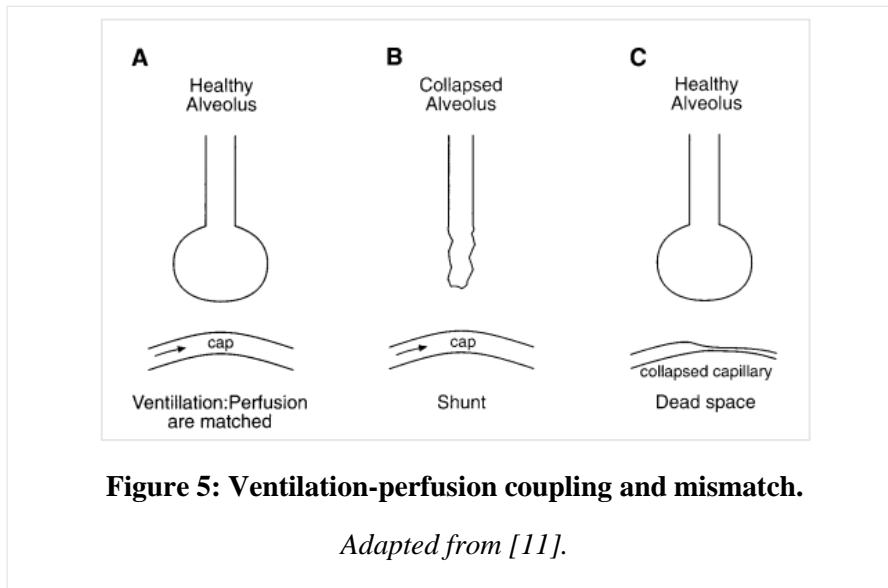
Atelectasis: Mechanisms and Sequelae

Functional residual capacity is reduced when a patient is under general anesthesia due to loss of traction in the chest wall, diminished function of the intercostal muscles and/or compression of the lung. Atelectasis, from the Greek *atelez* (imperfect) and *ektasiz* (expansion) is the loss of volume in the lungs due to partial or complete collapse of the small airways (alveoli).¹² The etiology of atelectasis can be chemical, physiological, or mechanical: absorption of alveolar air due to pressure gradientsⁱⁱ, impaired surfactant production or function, or compression of the lung tissue, respectively. A 1995 study found that 87% of human patients undergoing general anesthesia had evidence of atelectasis found on CT imaging.¹³ While not as thoroughly documented in veterinary medicine, it has been well established that atelectasis is the primary cause of impaired ventilation in anesthetized horses.¹⁴

The principle inspiratory muscle is the diaphragm, which is responsible for creating the pressure gradient that draws air into the lungs when it contracts. Compression atelectasis can result when the abdominal contents press against the diaphragm, preventing it from fully extending. This results in decreased transthoracic pressure and decreased lung volume, which in turn results in reduced gas exchange in the alveoli.

Ventilation-perfusion (V/Q) mismatch is the term used to describe the state in which the atelectatic alveoli cannot participate in gas exchange, but its associated capillary network is still functional. It can also occur in reverse, when the alveoli can expand but the vasculature is either constricted or otherwise compromised (See Fig. 5). In either case, the mismatch results in *intrapulmonary shunt*: blood entering the arterial circulation without complete oxygenation. Impaired oxygenation will result in hypoxemia ($P_{aO_2} < 60 \text{ mmHg}$) and hypoxia ($SpO_2 < 90\%$), which can result in tissue death, brain injury, and prolonged recovery.

ⁱⁱ While not a primary concern in this project, it should be noted that absorption atelectasis can occur during equine anesthesia, as one of the methods of treating hypoxia is to insufflate 100% FiO₂. This results in a washout of nitrogen in the lungs, which is much less soluble than oxygen and therefore primarily responsible for maintaining alveolar patency. When the partial pressure of alveolar oxygen (P_{AO_2}) increases with increased FiO₂, the oxygen rapidly shifts to the capillary blood and the alveoli collapse. Therefore, supplemental oxygen can actually exacerbate atelectasis when attempting to correct atelectasis-induced hypoxemia (J. O'Brien, 2013. Arzanipour & Heitz, 2016).



Atelectasis in the Equine Patient

Atelectasis begins to develop soon after anesthetic induction, particularly in the dependent lung fields.¹⁶ Placing these animals on their backs and hoisting them to the surgical table causes the abdominal contents to weigh against the diaphragm and the front legs to compress the rib cage. This causes a substantial strain on work of breathing even in a healthy patient that is likely to already have reduced respiratory drive due to anesthetic drugs. This effect is worsened in obese patients and in horses with heavier abdominal contents, such as in colic. Regardless of health status, atelectasis in the equine patient will have more severe effects and complications because of their unique respiratory anatomy and physiology.

Namely, when the horse is in dorsal recumbency the dependent lung fields are the most compressed but V/Q mismatch is worsened because that is the region with the most vascularization. Secondly, because every terminal bronchiole connects to an alveolar duct, horses have minimal collateral ventilation, and the collapse of these terminal bronchioles can cause the entire associated lung unit to be unable to participate in gas exchange. Finally, due to their biphasic breathing strategy, the depressive effects of gravity and anesthetic drugs significantly impair the horse's ability to maintain its FRC.

While atelectasis has not been specifically identified in the literature as a major culprit in anesthetic-related morbidity and mortality (ARMM), it should be noted that anesthetic-related

mortality in horses is approximately 1% - substantially higher than the risk in dogs and cats (approximately 0.23% and 0.29% respectively).¹⁷

Atelectasis: Treatment and Prevention

In uninjured lungs, the goal in the treatment of atelectasis is to maximize and maintain the functional residual capacity (FRC). The primary strategy, in human and veterinary medicine alike, is the use of alveolar recruitment maneuvers (RMs) followed by application of positive end-expiratory pressure. RMs are performed by providing applied increased pressure during inhalation to reopen (i.e. recruit) alveoli. The application of PEEP prevents collapse from recurring (i.e. decruitment). This is referred to as the *open lung concept* and can be done using higher FiO₂ to treat hypoxia. However, excessive or prolonged pressure can lead to barotrauma and ventilator induced lung injury (VILI).

RM, CMV, and PEEP in Equine Anesthesia

In much of the literature, hoisting- and anesthesia-related atelectasis seems to be deemed an unavoidable risk. In the first study of its kind, Cerullo, et al. (2020) found that horses experienced an average of 60% decrease in PaO₂ during the first ten minutes of hoisting and only returned to about 50% of its original value when placed in lateral recumbency.¹⁸ Therefore, anesthetists must use CMV measures (RM, PEEP) to reverse atelectasis and hypoxia that developed in the preoperative period. To date, little if anything is done to prevent atelectasis from developing in the first place despite the fact that it is much more difficult to open closed airways than to maintain open ones.

Unfortunately, RM and PEEP can come with unpredictable and deleterious cardiovascular effects in horses due to increased intrathoracic pressure. Positive pressure in the thorax can reduce cardiac output due to compression of the vena cava and reduced venous return. This in turn will result in a drop in blood pressure (hypotension), which can lead to other complications associated with reduced perfusion, such as post-anesthesia myopathy.¹⁹ Excessive positive pressure, which can occur due to the nonuniform distribution of ventilation in the lung tissue, can exacerbate the ventilation-perfusion mismatch if alveoli are overdistended and compress their associated capillary network. Additionally, CMV makes gas distribution more gravity dependent, moving ventilation into the nondependent lung fields, which are less perfused and compress than the dependent one.

Veterinary anesthesiologists perform these methods with extreme caution. Over the years, research has repeatedly addressed the conundrum of how to best assist ventilation in the anesthetized horse, yet there remains no “perfect” method or device to provide adequate ventilatory support with minimal cardiovascular impairment²⁰. Unfortunately, the first studies into these methods in the 1970s laid a poor foundation for later research. In fact, an often-cited 1975 study on the effects of PEEP in spontaneously breathing anesthetized horses concluded that “indiscriminate application of end-expiratory pressure has no place in routine equine anesthesia” citing decrease in ventilation and cardiac output.²¹ However, the subjects of the study were anesthetized with halothane gas, the use of which was discontinued in the early 1990s due to its dangerous side effects, including hypoventilation, myocardial depression and the associated decrease in cardiac output and arterial blood pressure.²² Also, the study noted that due to malfunctioning equipment, only 17 experiments out of 41 produced viable data and PEEP (which was created by submerging the expiratory tube in a bucket of water) was applied at least 30 minutes after induction.

Next Steps

In veterinary medicine, we often look to the vastly more developed practices of human medicine for answers. According to the WHO, worldwide obesity has nearly tripled since 1975.²³ One anesthetic complication in severely overweight patients parallels that in hoisted horses: compression atelectasis due to the weight of the abdominal contents on the diaphragm.²⁴ Anesthesiologists and bariatric physicians now recommend the application of PEEP before induction and after intubation as method for preventing atelectasis.²⁵ This strategy could potentially be applied in horses, but the equipment to do so doesn't exist (yet).

CHAPTER 3 – PROJECT STRATEGY

(Objectives & Constraints)

3.1 Initial Client Statement

“A device such as a bidirectional PEEP valve is needed to aid in the prevention of the onset of atelectasis in the recumbent anesthetized horse, specifically to be applied directly to the endotracheal tube after intubation that can later be connected to the anesthetic circuit.”

3.2 Design Requirements (Table 1)

OBJECTIVES	
Client’s Needs	Allow for bidirectional flow
	Adjustable levels of PEEP (5-30cmH ₂ O)
	Cannot inadvertently obstruct inspiration
	Universal size to fit directly to the end of an equine endotracheal tube (EETT)
	Easily removed in case of adverse event
	connects to tubing of the anesthetic machine
Based on Background Research	Malfunction should be easily detected and corrected
CONSTRAINTS	
Lower bounds of design parameters	52mm diameter to fit the inner diameter of the EETT
Upper bounds of design parameters	56mm diameter to fit the inner diameter of the EETT
SPECIFICATIONS	
Operational ranges	5 to 30cmH ₂ O positive pressure at the end of expiration
Tolerances	±5%
Degree of precision and/or accuracy	±5%
Materials	Lightweight plastic, ideally transparent Stainless steel spring

3.3. Design Requirements (Standards)

Engineering Standards (Table 2)

Minimum performance	The ETTYPEEP should provide PEEP at the prescribed level within 5%.
Safety requirements	The ETTYPEEP must be easily removed in the event of adverse reaction or malfunction.
Compatibility	The ETTYPEEP must fit onto a large animal endotracheal tube or the ETT adapter typically used.
Repeatability	The ETTYPEEP must be able to provide the same level of PEEP after repeated use.

Specifications

TABLE 3: ICS 11.040.01: MEDICAL EQUIPMENT IN GENERAL	
ISO	Description
13485:2016	Quality management systems -Requirements for regulatory purposes
14971:2019	Application of risk management to medical devices
15223-1:2016	Symbols to be used with medical device labels, labelling and information to be supplied — Part 1: General requirements
16142-1:2016 16142-2:2017	Recognized essential principles of safety and performance of medical devices — Parts 1&2: General essential principles and additional specific essential principles for all non-IVD medical devices and guidance on the selection of standards
20417	Information to be supplied by the manufacturer

TABLE 4: ICS 11.040.10: ANESTHETIC, RESPIRATORY, AND REANIMATION EQUIPMENT (INCLUDING MEDICAL GAS INSTALLATIONS)	
ISO	Description
4135:2001	Anesthetic and respiratory equipment — Vocabulary

5361:2016	Tracheal tubes and connectors
15001:2010	Compatibility with oxygen
18190:2016	General requirements for airways and related equipment
80601-2-79:2018 80601-2-80:2018	Part 2-79,80: Particular requirements for basic safety and essential performance of ventilatory support equipment for ventilatory impairment

TABLE 5: ICS 11.220: VETERINARY MEDICINE (INCLUDING EQUIPMENT SPECIFIC TO VETERINARY MEDICINE)	
ISO	Description
https://www.iso.org/ics/11.220/x/	

3.4 Revised Client Statement

“A Y-piece with a unidirectional inspiratory arm and an expiratory arm with an adjustable PEEP valve is needed to aid in the prevention of atelectasis in the recumbent anesthetized horse. It should fit securely to the endotracheal tube after intubation and be removed prior to connection to the anesthetic circuit or mechanical ventilator. It should be adjustable to provide 5-30cmH₂O of pressure at the end of expiration.”

3.5 Management Approach

TABLE 6: MQP TASK SCHEDULE			
Milestone	Associated activities	Begin By	End By
Complete literature review	Equine Respiratory Anatomy and Physiology	September 7, 2020	October 16, 2020
	Pulmonary atelectasis (etiology, mechanisms)		
	Pulmonary atelectasis (prevention, treatment)		
	Mechanical ventilation (RM, IPPV, PIP, etc.)		
	Equine Anesthesia		
Observe at least one equine anesthetic procedure at Tufts	Time procedures (including intubation, hoisting, total anesthesia),	November 1, 2020	December 1, 2020
	measure equipment (AC, ETT)		
Solidworks Design	Learn 3D printing procedure at Foise	December 1, 2020	February 1, 2021
Print prototype parts	Verify fit with EETT	February 2, 2021	March 1, 2021
Finalize testing and calibration procedure with equine ventilator at Tufts	Write testing protocol, take photos of setup	March 1, 2021	March 24, 2021
	Verify methods with Dr. Liao and Dr. Savilonis	March 20, 2021	April 1, 2021
MQP Report Draft		March 1, 2021	March 18, 2021
Final MQP Report Submission	Include eCDR and ABET Audit Sheet		May 7, 2021

CHAPTER 4 – DESIGN PROCESS

4.1 Needs Analysis

A systematic, pairwise comparison of the design objectives was done to prioritize design specifications (see Table 6). Each objective in the column on the left was scored -1 (less important) or 0 (equally important) or +1 (more important), in comparison to the objectives in the top row. The initial requirement for the device to connect to the anesthetic circuit was omitted after discussion with Dr. Liao. This analysis led to the conclusion that the device would need to fulfill objectives A, E, and F, while the other three would be secondary.

Objectives:

- A. Fits large animal endotracheal tube
- B. Durable
- C. Sterilizable
- D. Inexpensive
- E. Adjustable PEEP
- F. Allows for bidirectional flow

Objective	A	B	C	D	E	F	total
A	-	+1	+1	+1	0	0	+3
B	-1	-	0	+1	-1	-1	-2
C	-1	0	-	+1	-1	-1	0
D	-1	-1	-1	-	-1	-1	-5
E	0	+1	+1	+1	-	0	+3
F	0	+1	+1	+1	0	+1	+3

4.2 Conceptualization

4.2.1 Concept Map

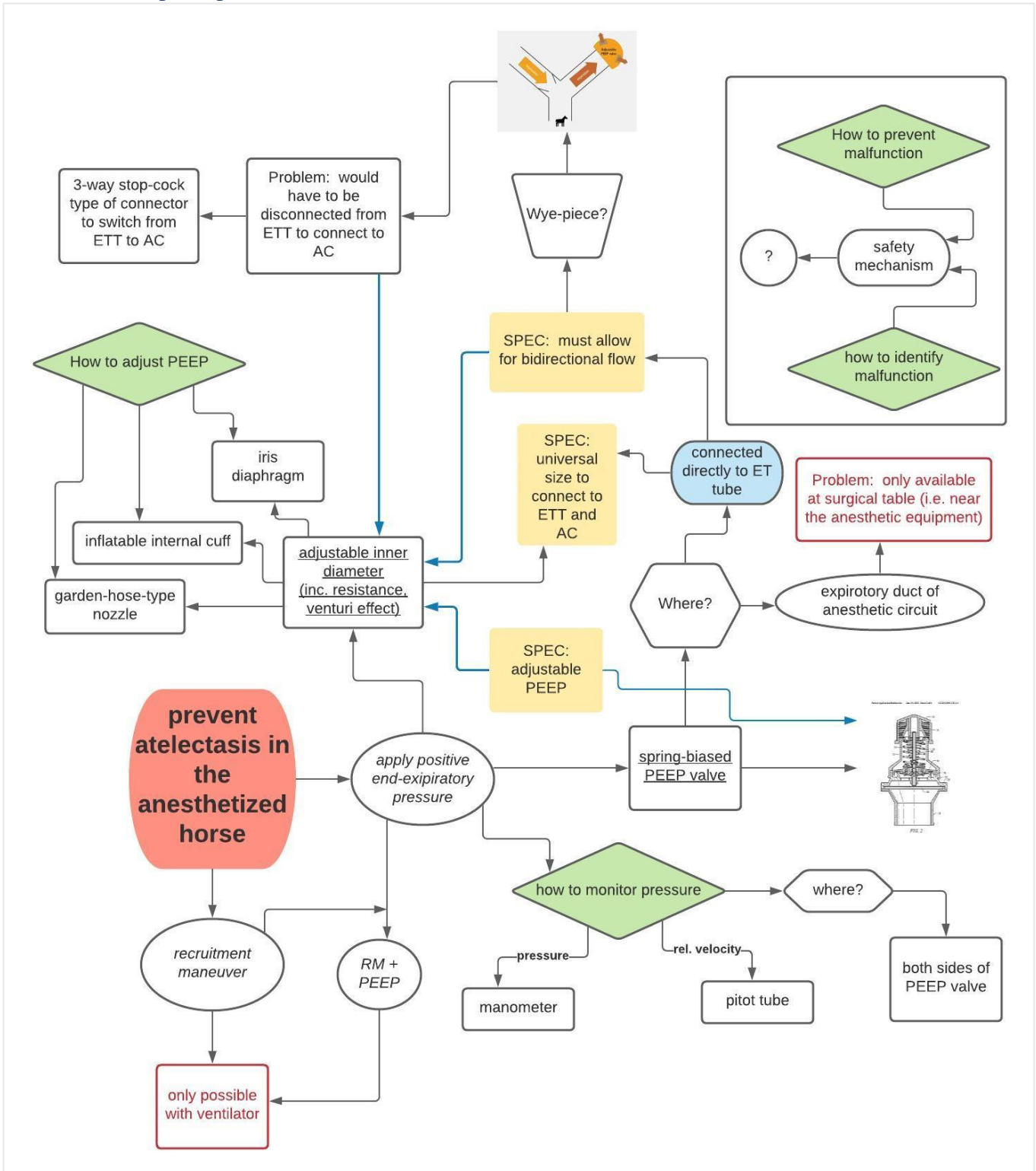


Figure 6: Concept Map Constructed during BME 4300 (MQP Capstone Design)

4.2.2. Conceptual Designs

Initial conceptualization of the EETYPEEP focused on the objective to allow for bidirectional flow. This was achieved by modifying the traditional Y-piece that is used to connect the endotracheal tube to the anesthetic circuit. The basic design has three arms: one to connect to the ET tube, one for expiratory flow (and application of PEEP) and one for one-way inspiratory flow. Several ideas for the PEEP valve and unidirectional inspiratory valve are outlined in the Section 4.3.

4.2.3 Design Concept Modeling/Prototyping

4.2.3.1 Y-Piece

Prior to building Solidworks models, a Y-piece was constructed using 2-inch polycarbonate tubing (purchased from Amazon.com) and hot glue (See Fig. 7). The angle of the arms was decided to be too large (approximately 120°) as it would create too much resistance to air flow.



Figure 7: Proof of Concept Prototype

To verify the precise measurements of the Solidworks models, I borrowed an equine endotracheal tube from the anesthesia department at the Tufts University, Cummings School of Veterinary Medicine. I used a digital caliper to measure the inner diameter of the bell of the ET tube, which is made of firm silicone rubber that allows for a few millimeters of stretch (See Fig. 8). Using this measurement, I created the Y-piece in Solidworks with an outer diameter to match the inner

diameter of the ET tube bell. One arm is shorter than the other to accommodate the PEEP-valve and adapter (see Fig. 9).



Figure 8: Measurement of Inner Diameter of ETT Bell

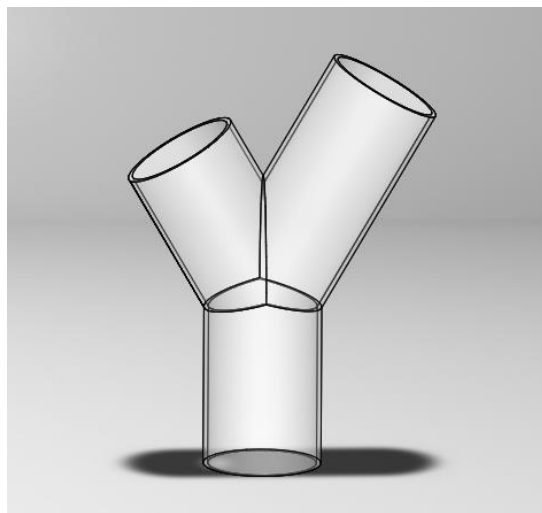


Figure 9: Y-Piece Model created in Solidworks

4.2.3.2 Equine PEEP Valve

Next, I created models of the expiratory valve components using a standard disposable 30mm PEEP valve (purchased from Coast Biomedical Equipment, Vista, CA) as a model (see Fig. 10 & 11). The three components include a main connection piece, expiratory diaphragm, and a threaded PEEP cap (see Fig. 12-15). The expiratory diaphragm covers the outlet on the main connection piece and has a raised center to hold the compression spring. To calculate the precise spring rate needed to convert cmH₂O to Newtons per square millimeter (N/mm²). 1 cmH₂O is equal to 9.8×10^{-5} N/mm². This number multiplied by the area of the expiratory outlet (1901 mm²) is the force needed to create 1cmH₂O. Using this force (0.186N), I searched for springs with the appropriate dimensions and a spring rate of 0.186N/mm so that for every millimeter the spring is depressed 1 cmH₂O is applied to the expiratory diaphragm. The spring I purchased from TheSpringStore.com (Acess Spring, Colton, CA) has a spring rate of 0.182N/mm. To make adjustments and calibration easier, I designed the cap with threads 5mm apart so that each 360° turn would increase the PEEP by 5cmH₂O.



Figure 10: Allied Healthcare External Peep Valve and 19mm valve adapter

Image source: CoastBiomed.com

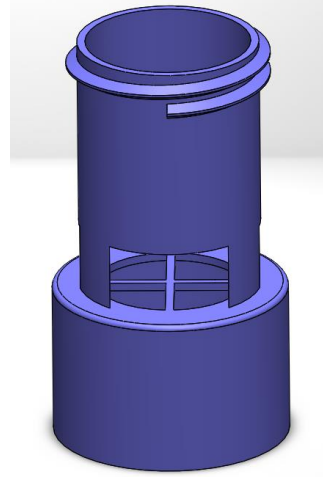


Figure 12: Main Connection Component for PEEP Valve

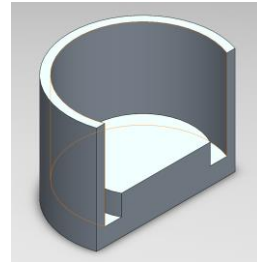


Figure 13: Expiratory Diaphragm
Shown in cross-section to display spring holder.

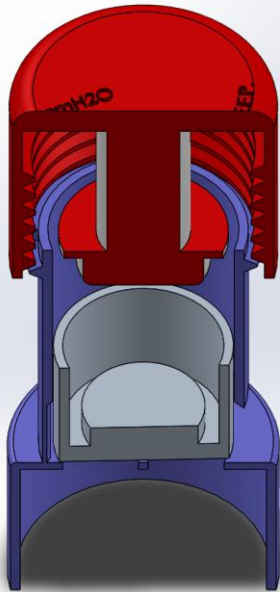


Figure 11: Solidworks Model of PEEP Valve for ETTY PEEP.
Shown in cross-section. (Spring not modeled.)

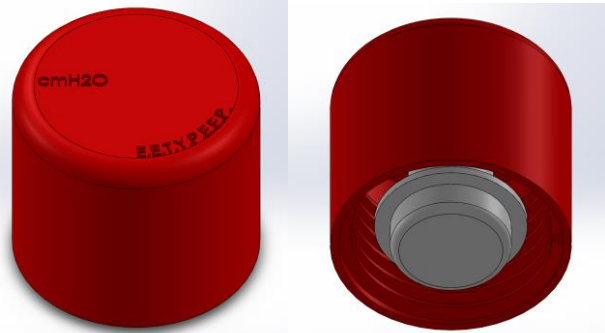


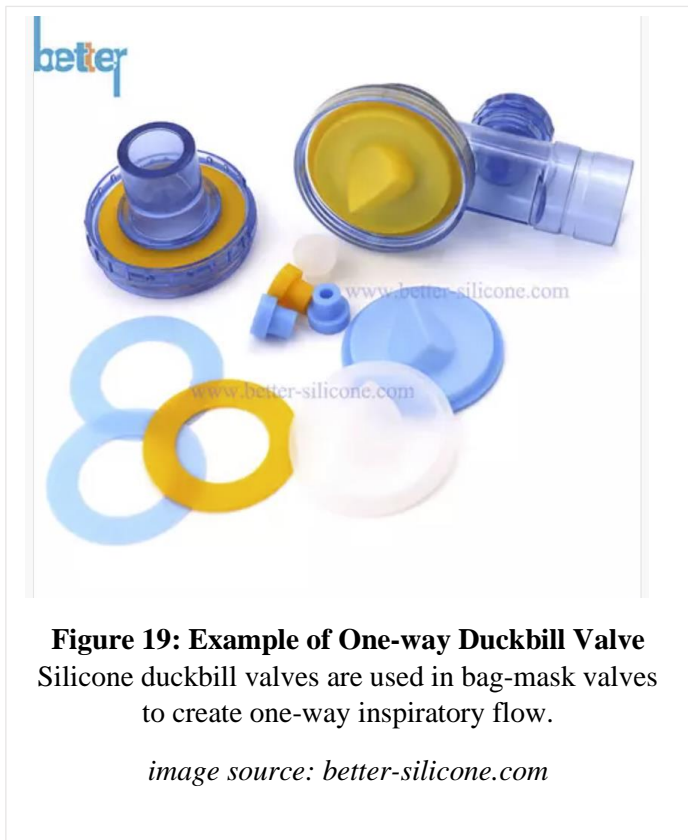
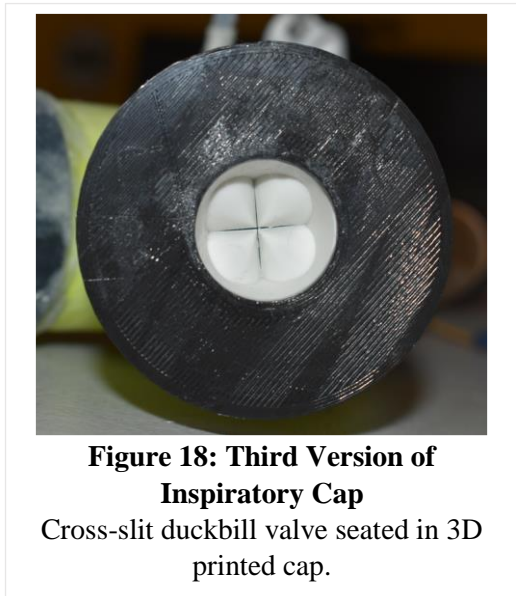
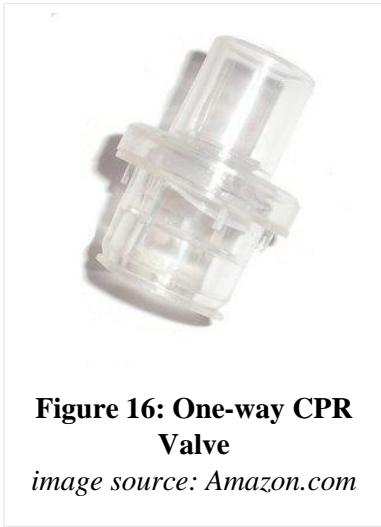
Figure 14: Threaded PEEP Valve Cap
Shown from above and below

4.2.3.3 One-way Inspiratory Cap

For the PEEP valve to hold pressure at the end of expiration, it was necessary to design a one-way valve for the inspiratory arm that would close during exhalation. The first version was simply a cap with cross bars and a silicone diaphragm attached in the center (see Fig. 15). Preliminary testing showed that this design was unable to maintain a seal at the low pressure of exhalation, so a second version was made using the one-way valve used in CPR masks as a model (see Fig. 16). These valves allow for one-way flow using a thin shield-shaped silicone membrane attached to inner surface of the outlet. To achieve this, I designed an adapter to fit on the end of the inspiratory arm and a cap that would hold the silicone membrane (see Fig. 17). I purchased a sheet of 1.6mm silicone from Amazon for the membrane and made a template in Solidworks to make the cut-out the exact shape to fit in the cap. Unfortunately, even after the addition of silicone caulk at the seams, this version also failed to create an air-tight seal. Due to time constraints, the third version was constructed using a sample valve from minivalve.com (see Fig. 18). This silicone cross-slit valve had a diameter of 27mm, so it was insufficient for inspiratory validation testing. However, was able to maintain an airtight seal, making expiratory pressure testing possible. This type of valve is a good choice for future models, as it is similar to the one-way duck-bill valves used in bag-mask valves (see Fig. 19).



Figure 15: First Version of Inspiratory Cap
Second photo shows the insufficient seal. The silicone membrane is attached at the center with fishing line.

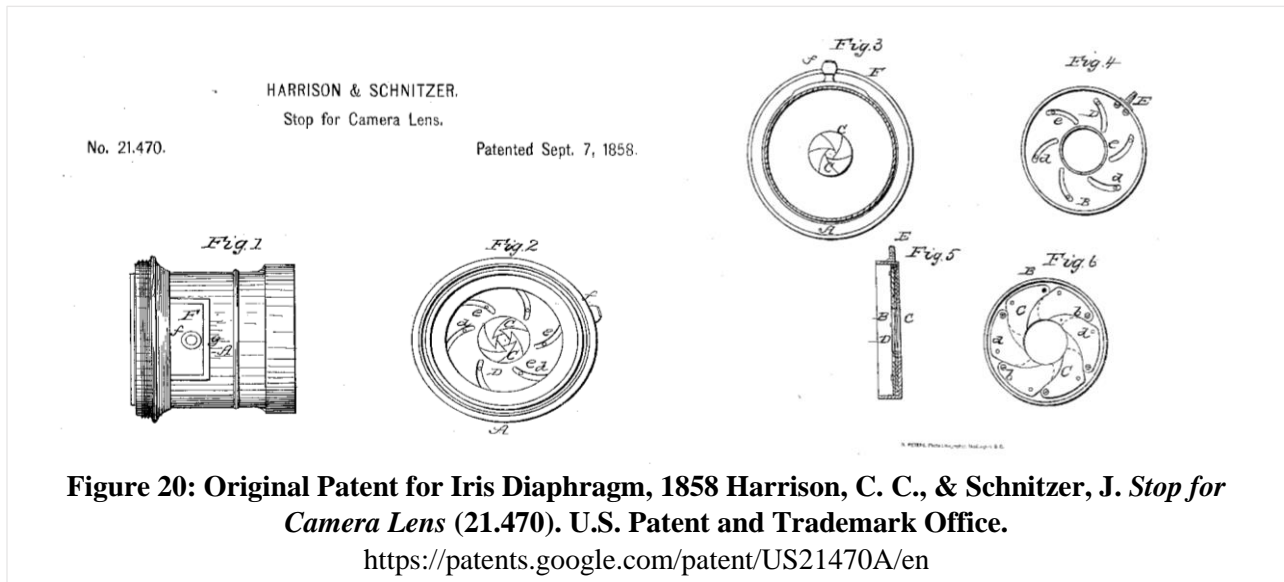


4.3 Alternative Designs

During the conceptualization phase of this project, I considered several alternative designs (see Fig 6 on page 22). First, I considered novel ways of creating positive end-expiratory pressure. My first thought was to create resistance by narrowing the expiratory outlet. This could be accomplished with the use of an iris diaphragm. I also explored several options for the one-way inspiratory valve and explored the option of a ball-in-cage design similar to the prosthetic heart valves, and an original design similar to the ball-in-cage that I called the “parachute valve.”

4.3.1 Iris Diaphragm Peep Valve

Figure 21 shows the patent for an iris diaphragm, originally designed to adjust the amount of light let through a camera lens.²⁶ The center aperture is made smaller or larger by turning an internal disc on which several curved “blades” swivel in unison. In theory, the same design concept could be applied to the expiratory arm of the Y-piece to create resistance and thus positive pressure. This design concept was rejected because the pressure needs to be provided at the end of expiration and creating resistance would merely increase the work of breathing.



4.3.2 Heart Valve Prosthesis-Inspired Designs for One-way Inspiratory Valve

I researched several types of one-way valves for the design of the inspiratory arm. The ideal valve would cause no resistance during inhalation. I considered the ball-in-cage design used in artificial heart valves (see Fig. 21), as resistance in that application could have terrible consequences²⁷. Similarly, the bileaflet aortic valve prosthesis (Fig. 22) could have been a model for one-way flow. Working from these models, I created a prototype one-way valve using a ping-pong ball cut in half and tethered to a plastic ring

(see Fig. 23) in a “parachute” design that would close the inlet during exhalation. These ideas were rejected, however, because of the potential for the valve to close if the device is upside-down, which would impede breathing.

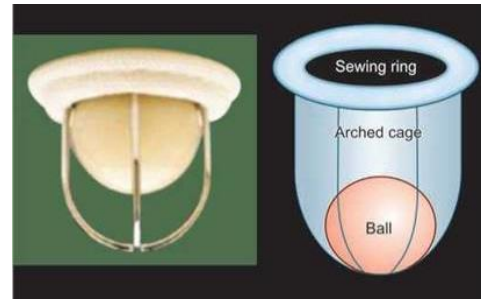


Figure 21: Model and Diagram of a Ball-in-Cage Aortic Valve Prosthesis

Adapted from [25]



Figure 22: Aortic Valve Bileaflet Prosthesis

*Image source:
medicalexp.com*

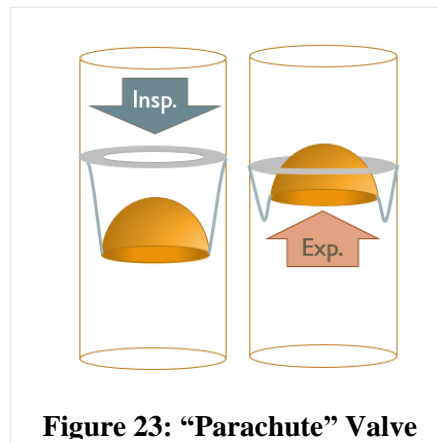


Figure 23: “Parachute” Valve

CHAPTER 5 – FINAL DESIGN AND VALIDATION

Creating the 5-30cmH₂O PEEP settings would require the simulation of equine exhalation (a tidal volume of 5-6 liters over 2-3 seconds). The initial concept for testing involved the use of a large animal ventilator at the Tufts University Cummings School for Veterinary Medicine with the help of a coworker, Matthew Dann, CVT (a board-certified veterinary anesthesia technician) (see Fig. 24). Initial testing was done by connecting the endotracheal tube to a three-way adapter connected to the inspiratory outlet of the ventilator (see Fig 26). A 30L large animal breathing bag was used to simulate a “single alveolus” and the maintained volume at the incremental levels of PEEP. The pressure created was to be monitored within the EETYPEEP using a digital manometer (see Fig. 27). Sustained pressure levels would be used to create the PEEP level settings.



Figure 24: Large Animal Ventilator



Figure 25: Initial Testing Apparatus



Figure 26: Large Animal Breathing Bag

Unfortunately, we encountered several obstacles that made this testing method unreliable. Primarily, the ventilator's built-in safety mechanisms made it impossible to create a sustained level of pressure. Secondly, because it was a volume-controlled ventilator, it was designed to deliver a volume of air at a constant rate. Normal exhalation exhibits an exponential decay in pressure, but this machine would have done the opposite. Due to time constraints, a new testing method had to be developed using limited materials.

The new testing apparatus included a 1.75-inch diameter polycarbonate tubing to hold the ET tube, a 3D-printed adaptor to connect the ET tube to two 3L breathing bags, and an air-mattress pump (see Fig. 27). The 3D-printed adaptor was initially designed to be used with the ventilator, so one end was closed using a 3D-printed cap (the white component in Fig 27), that had originally been designed to seal the expiratory outlet of the ventilator. All seams were sealed with silicone caulk and the entire apparatus was sprayed with a rubberized coating (LeakSeal® by Rust-oleum) to prevent leaks. The seal was tested by spraying the apparatus with soapy water and observing for any bubbles when the system was pressurized.



Figure 27: Second Testing Apparatus
Two 3L breathing bags were inflated using an air mattress pump.

Due to the poor test quality, this method was only used to determine if the EETYPEEP valve was able to hold incremental levels of pressure at incremental levels of spring compression. This was achieved by pressurizing the system with the air mattress pump while the valve cap was closed and then loosening it in 90° turns and recording the change in pressure. During the first trial, it was clear that while the EETYPEEP valve was able to maintain a somewhat linear relationship between pressure and compression at higher level, it was less stable at lower pressures. Additionally, the readings may be erratic due to the material irregularity. As seen in Figure 28, the 3D-printed outlet diaphragm has small ridges, making the seal incomplete. To mitigate this issue, I added a disc of 1.6mm silicone to the diaphragm. While this did improve the valve performance, the air pump

caused irregular pressure levels between each level. The comparative results can be seen in Figure 30.



Figure 28: 3D-Printed Outlet Diaphragm (left) compared to the medical grade version (right)
 The 3D printing process creates ridges in the material, while injection molding does not.

TABLE 8: OBJECTIVE VALIDATION RESULTS		
OBJECTIVES	METHOD OF VALIDATION	ABLE TO VALIDATE? (Y/N)
Allow for bidirectional flow	Simulate inhalation and measure any resistance to flow within the EETYPEEP and/or ET tube	N
Adjustable levels of PEEP (5-30cmH ₂ O)	Simulate the exponential decay and volumetric flow rate of equine exhalation and monitor the pressure maintained at the end of the breathe. Verify that the settings maintain the PEEP within 5%	N
Cannot inadvertently obstruct inspiration	Verify that the inspiratory valve function is independent of position	Y

Universal size to fit directly to the end of an equine endotracheal tube (EETT)	Verify that the inner diameter of the equine ET tube matches the outer diameter of the EETYPEEP.	Y
Easily removed in case of adverse event	Verify easy removal with 2 seconds from various positions.	Y

6.1 Economics

The results of this project will not likely influence the economy of everyday living. With respect to the specific economics of equine medicine, the EETYPEEP could potentially reduce the risks and negative effects of anesthesia as outlined in previous chapters. These benefits could reduce costs associated with anesthetic and recovery procedures.

6.2 Environmental Impact

The most significant impacts this device could potentially have on the environment are primarily related to the manufacturing process. Unlike human medicine, veterinary medicine regularly sterilizes and reuses equipment, which can cut down on the impact associated with single-use devices.

6.3 Societal Influence

This device will have negligible impact on general society.

6.4 Political Ramifications

This product will very likely not influence the global market or the culture of other countries. That said, cultures that rely more heavily on horses for everyday life may have more interest in the EETYPEEP.

6.5 Ethical Concerns

The ethical concerns associated with the EETYPEEP are limited to those that are addressed by the Veterinarian Oath. Upon licensure, veterinarians and veterinary technicians swear to protect

animal health and welfare and to prevent and relieve animal suffering. This device is a tool towards that aim.

6.6 Health and Safety Issues

As described in the preceding chapters, the ETTYPEEP is designed to reduce the risk of atelectasis in anesthetized horses, thereby improving their health and safety.

6.7 Manufacturability

The ETTYPEEP can be reproduced by additive or injection-molding manufacturing. Its relatively simple, tubular design will make manufacturing relatively simple. The spring of the PEEP component can be mass produced.

6.8 Sustainability

The sustainability of the production of the ETTYPEEP will depend on the facility in which it is manufactured. Ideally, it could be produced with post-consumer materials and the manufacturing process could be designed to have minimal to no carbon footprint.

CHAPTER 6 – DESIGN VERIFICATION

Due to unforeseen limitations and complications caused by the COVID-19 pandemic, I was unable to verify the function of the EETYPEEP valve. This was primarily due to restricted access to campus facilities and limited time for retesting after the first method failed (see Chapter 6). Nonetheless, this chapter outlines the data collected from the *ad hoc* testing method, which was unable provide repeatable results. I have also included those methods that *would* have been used to verify the design and the appropriate data analysis under better circumstances.

5.1 Data from *ad hoc* Testing

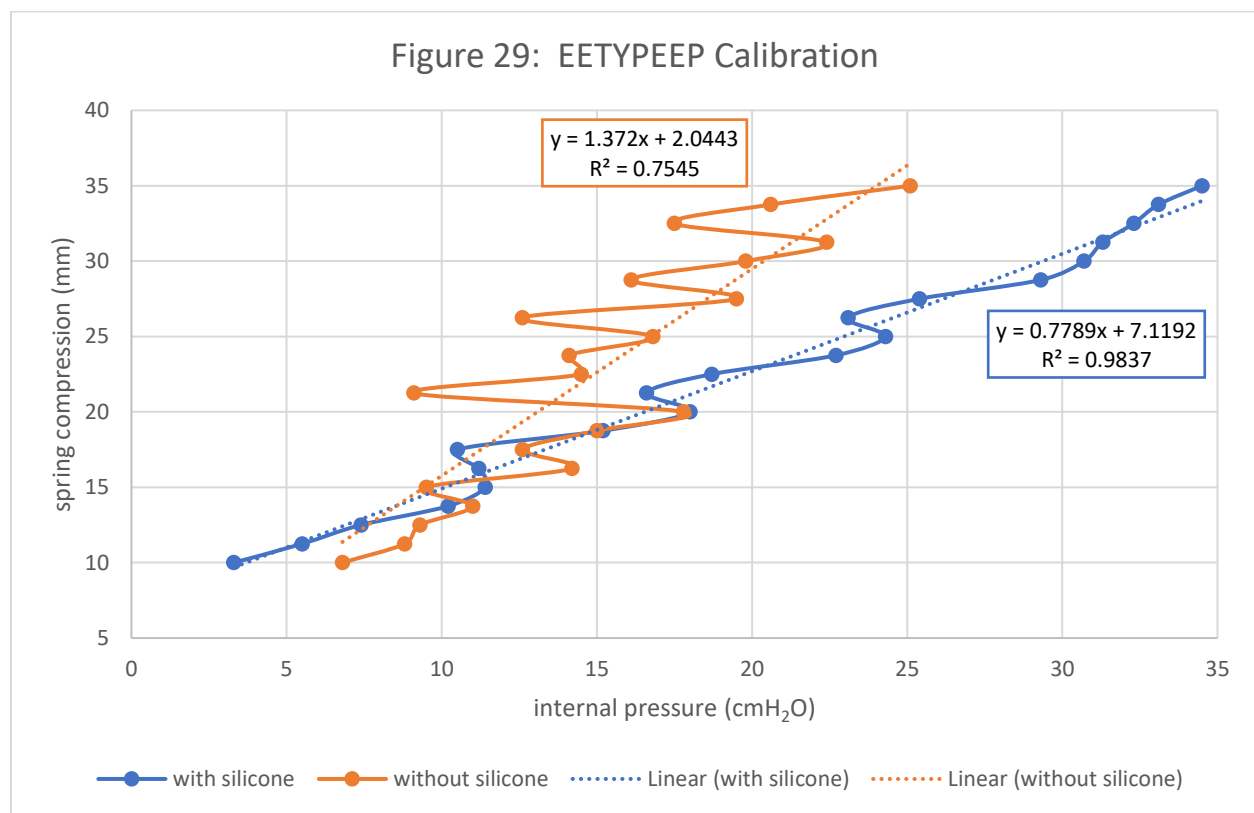


Figure 29 displays the internal pressure readings found using the methods outlined in Chapter 5. The interference from the vibrations of the air mattress pump, combined with the incomplete seal due to the ridges in the 3D-printed material, caused the readings to oscillate (as seen in the orange data in Fig. 29). The addition of a silicone disc between the outlet and the PEEP valve diaphragm greatly improved the results, however the readings continued to be inconsistent.

5.2 Suggested Data Collection and Analysis Methods

1. Perform multiple trials of the equine exhalation simulation (e.g. 5.6L over 2.4 seconds) to compare with in vivo equine lung function testing to determine accuracy for testing the EETYPEEP.
 - a. Verify simulation accuracy within a 10% margin.

2. Use equine exhalation simulation to create the PEEP settings in 5cmH₂O increments. Repeat to verify maintained pressure at each setting.
 - a. Calculate mean and standard deviation for each setting.
 - b. Correct excessive error with redesigned components and repeat testing to maintain error with a 5% margin.

3. Perform multiple trials of equine inhalation simulation to record the resistance within the ET tube and in the EETYPEEP and compare with resistance without the inspiratory valve.
 - a. Calculate mean and standard deviation for each trial.
 - b. Perform t-test to determine the statistical significance of the mean measured resistance.

CHAPTER 7 – DISCUSSION

Compression atelectasis in recumbent anesthetized horses has been deemed an unavoidable complication for decades despite the potentially lethal consequences. The goal of this MQP was to develop a device to prevent atelectasis in recumbent horses. While this goal was not fully achieved, the undertaking of this project is a success as this concept had never been explored before.

The primary objectives of the device were to attach to the equine endotracheal tube, allow for unimpeded inspiration, and provide positive pressure at the end of exhalation between 5 and 30cmH₂O. The bag-valve mask (e.g. the AMBU bag) is the only comparable device on the market, so its various components were used as models for the design of the EETYPEEP valve. While the overall design was sound in theory, the testing methods using the equine ventilator to simulate exhalation failed. Due to the limited resources and time available, the ad hoc testing method using an air mattress pump was only able to provide minimal data that was not consistently reproducible. However, the moderate linearity of this data provides some evidence that with improved testing methods, the linear relationship between spring compression and end-expiratory pressure could be verified.

To truly validate and verify this device, an accurate simulation of equine breathing needs to be created. This would provide the exponential decay of pressure during exhalation, which can be modeled graphically to visualize the point at which PEEP is established. To achieve the goal of unimpeded inhalation, the simulation would provide data on significant resistance within the system. Modeling biological mechanics is exceedingly complex; therefore some assumptions must be made. These would include the negation of interference from motion, simplification of the complex equine breathing strategy, and assuming that the composition and properties of the gas in the system won't greatly affect the performance.

In the context of the COVID-19 pandemic, success in this project needed to be redefined. While the specific design objectives were not achieved, I do not consider this project a failure but rather a beginning.

CHAPTER 8 – CONCLUSIONS AND RECOMMENDATIONS

This MQP was born of the desire to increase the presence of veterinary medicine in biomedical engineering. There are countless problems in veterinary medicine that need gold-standard solutions. Atelectasis in recumbent horses is a prime example of such a problem. While this problem has been known for decades, the precarious nature of equine anesthesia and seems to make it a realm exclusive to anesthesiologists. This MQP is an attempt to breach that barrier for the greater good of veterinary medicine.

The results of this project are not the ideal outcome I had hoped for, but science rarely has ideal outcomes. COVID-19 certainly proved to create several challenges that I did my best to overcome with the resources available to me. My team – primarily Matthew Dann and Dr. Ben Liao – provided great insight into the mechanics of equine ventilation (both natural and mechanical). The initial testing methods (using the equine ventilator) were deemed a good idea all around until the build-in safety mechanisms made testing impossible. It is a lessons hard learned that a Plan B should always be part of a project strategy.

It was a risk to take on such a huge problem with practically no research model to use as a guide. That risk was multiplied by doing it without a traditional team and during a global pandemic. I would like to think that the greatest accomplishment is laying the groundwork for a project that could potentially solve a real world problem that currently has no solution. I would also hope that such a project could raise awareness of the need for more biomedical engineering in veterinary medicine.

The ETTYPEEP deserved further investigation, certainly with improved materials and testing methods. This is an opportunity to look to other engineering departments for input on the best construction methods and materials for the EETTYPEEP valve and for the equine breathing simulation. The following list includes my suggestions for future work and improvements based on the lessons I learned this year.

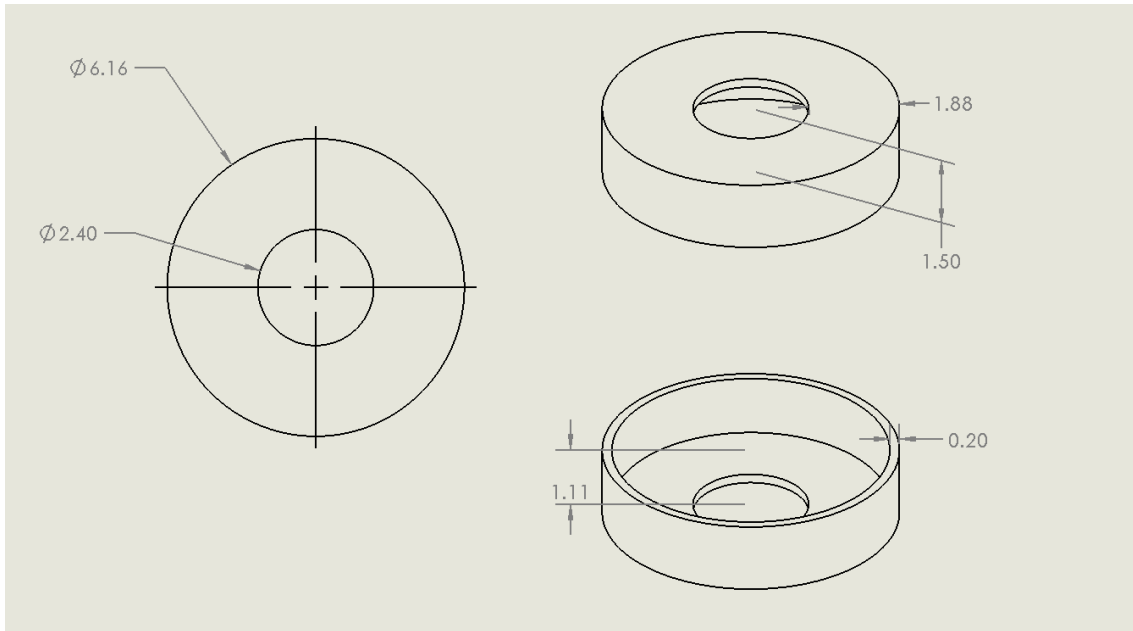
1. Because the 3-D printed material was not smooth enough to create a sufficient seal, it would be better to use prefabricated or injection-molded components. This will be a challenge due to the precise measurements required. 3-D printing could still be a viable option with improved resolution or post-printing treatment to smooth the surfaces.
 - a. Prefabricated silicone valves are available from online vendors, but may be too small for the ETTYPEEP. This problem could potentially be solved by designing a scaled-up mold in which a silicone valve could be made.
2. Build a pressure transducer and a flow meter, such as those used with the LoggerPro software, to measure and record pressure and flow changes in real time.

3. Work with the Mechanical Engineering department to design and build an equine breathing simulation that could possibly incorporate a pressure-controlled bellows-type system (similar to a ventilator) to accurately model the exponential decay of exhalation.
 - a. This system could also be used to model inhalation to test the resistance caused by the one-way inspiratory valve.
 - b. Future designs could also model the horse's biphasic breathing strategy.
4. Future work could also include analysis of typical horse body weights to determine the average weight of the abdominal contents that presses against the diaphragm when the horse is hoisted and placed in dorsal recumbency. A model could be built to test the ability of the EETYPEEP to perform to the prescribed standard under such conditions. This should include a model to visualize the maintained FRC when PEEP is applied.

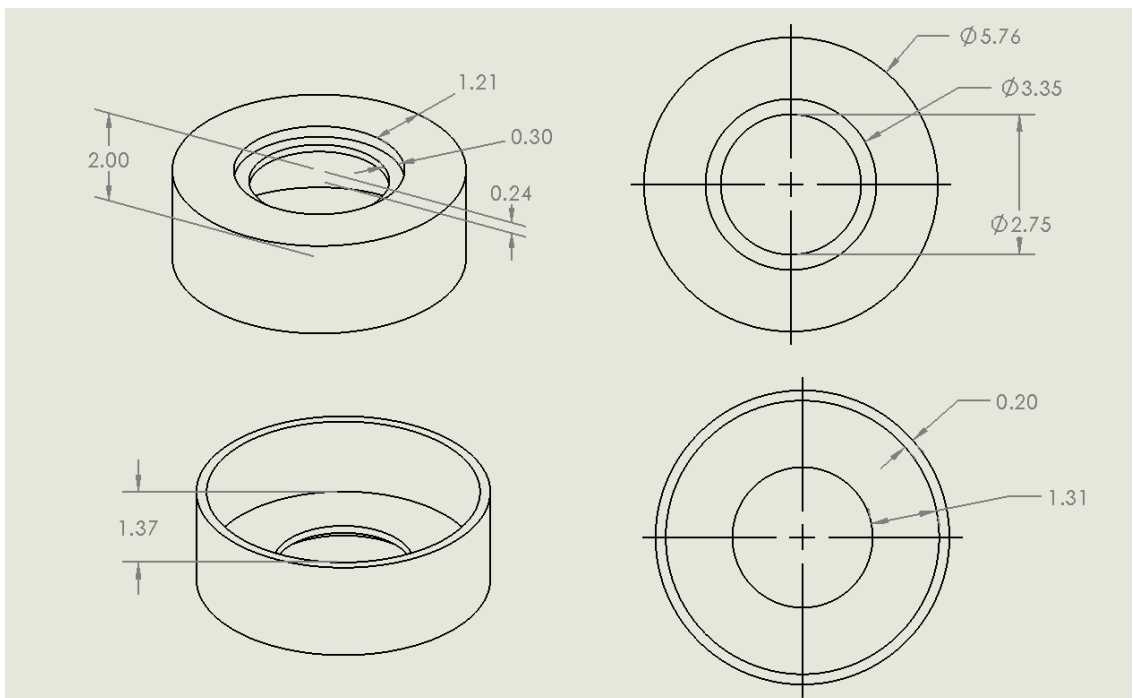
Appendix A: CAD Drawings of Final ETTYPEEP Components

Measurements are in centimeters.

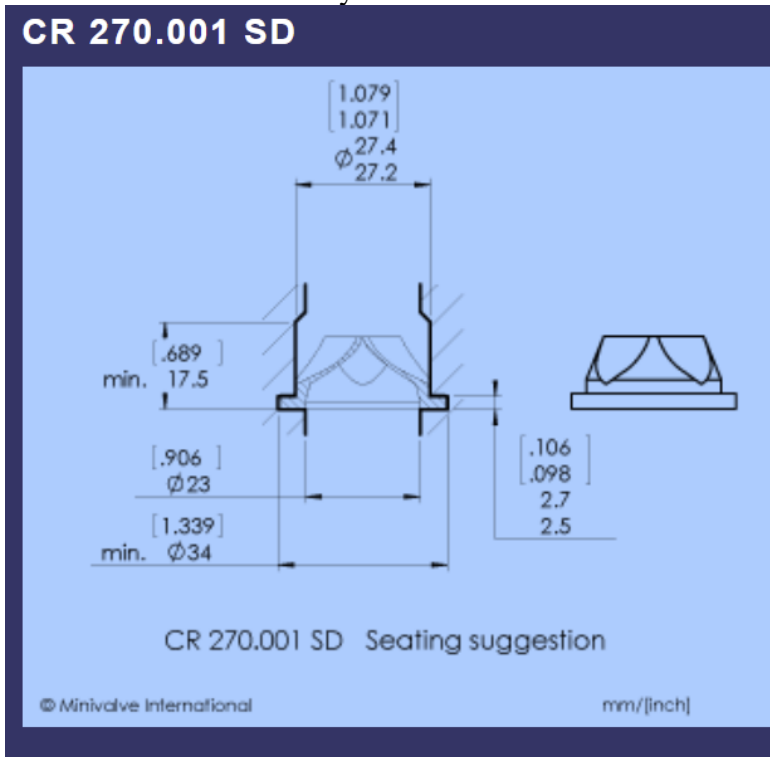
1. Exterior Inspiratory Cap



2. Interior Inspiratory Cap



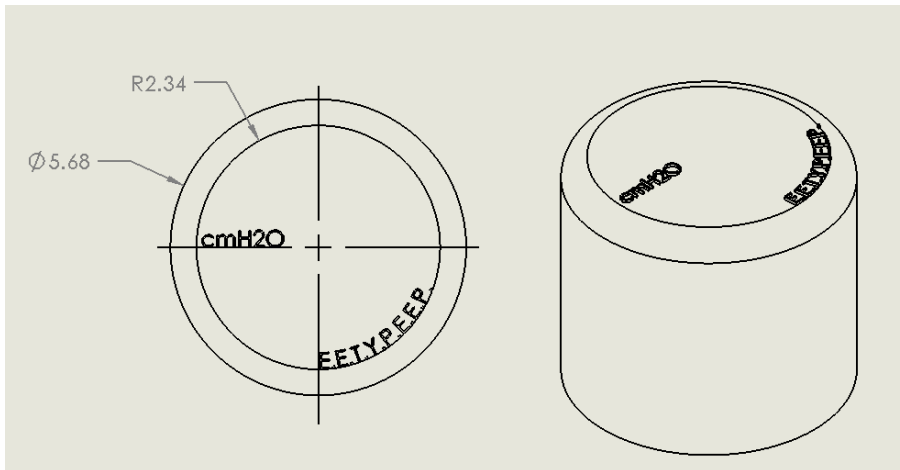
3. 27mm Cross-Slit One-Way Valve

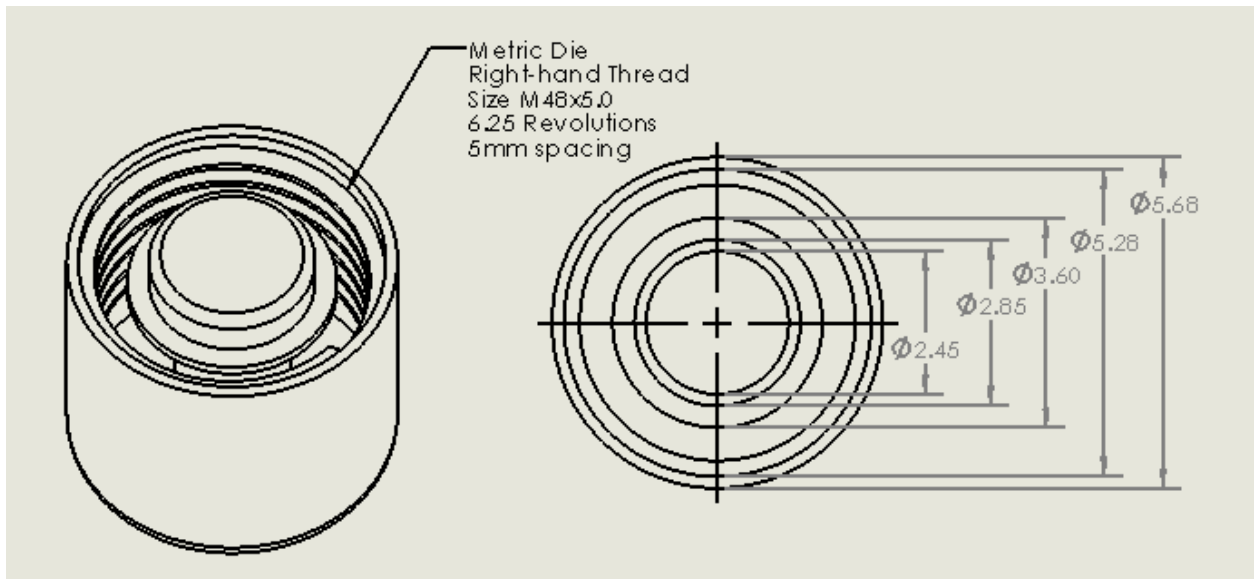
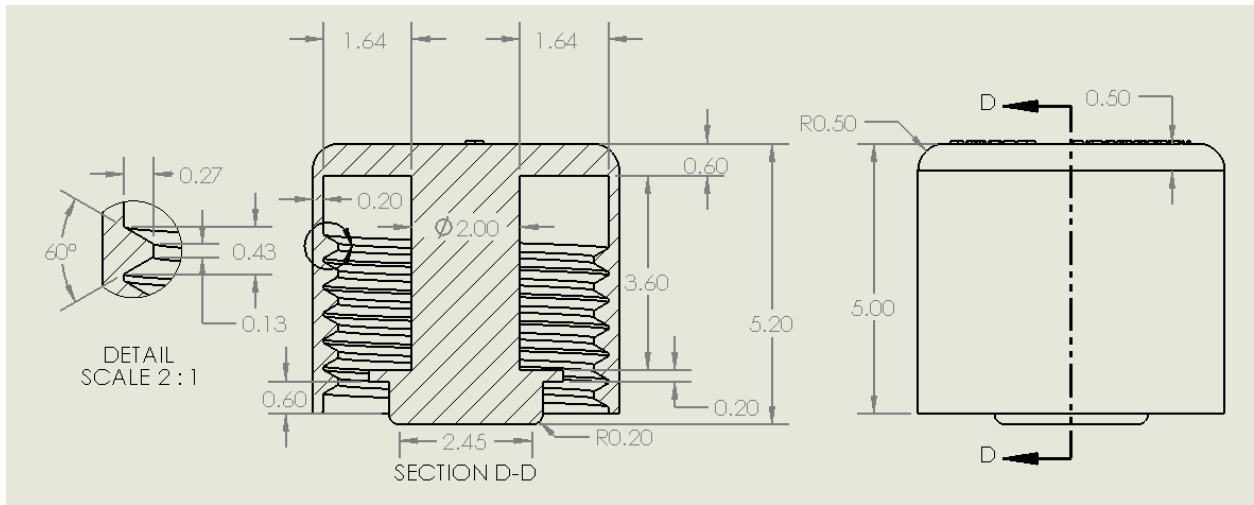


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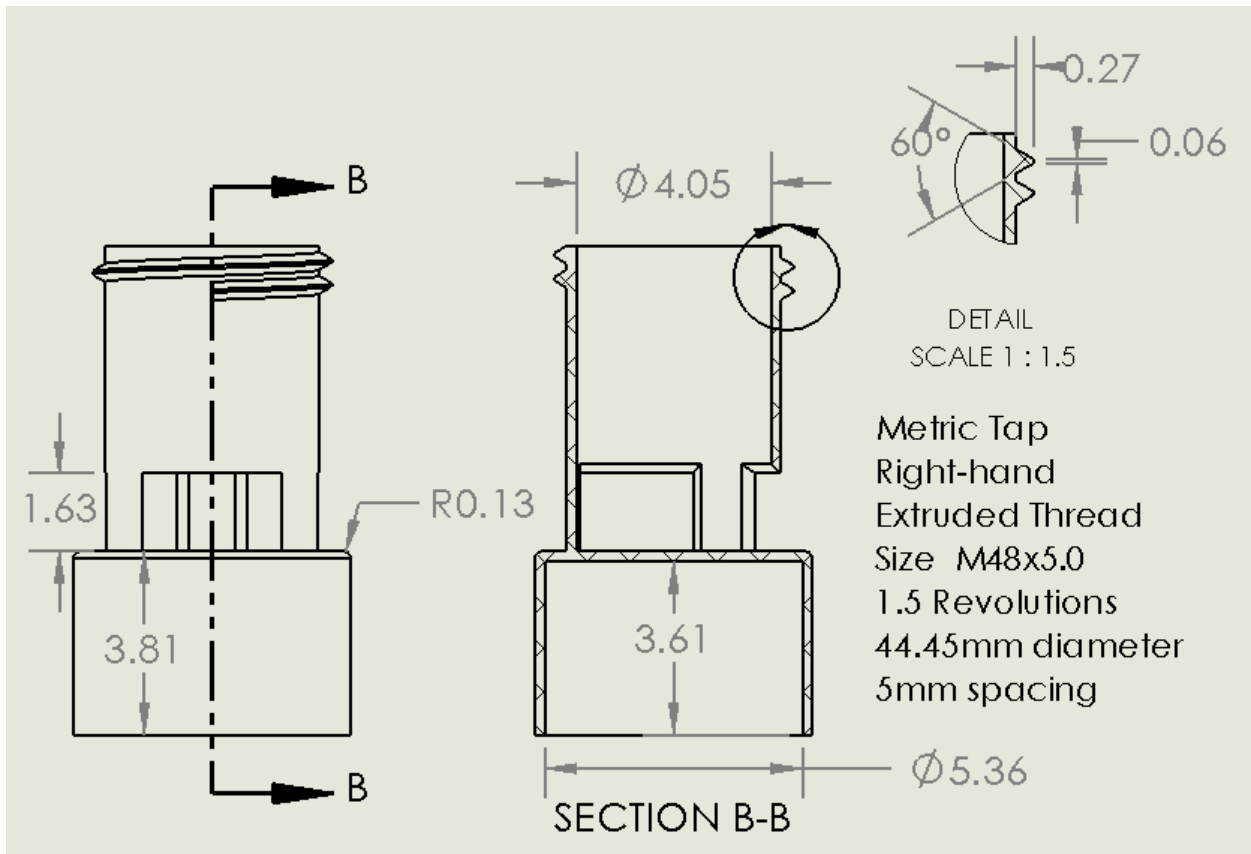
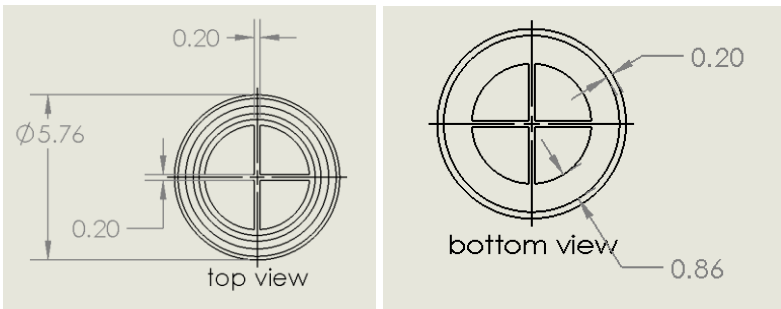
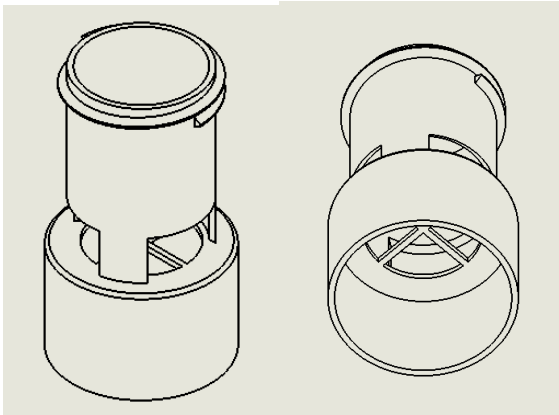
http://www.minivalve.com/newsite/?option=com_minivalve&product=75&view=minivalve&lang=en&Itemid=63

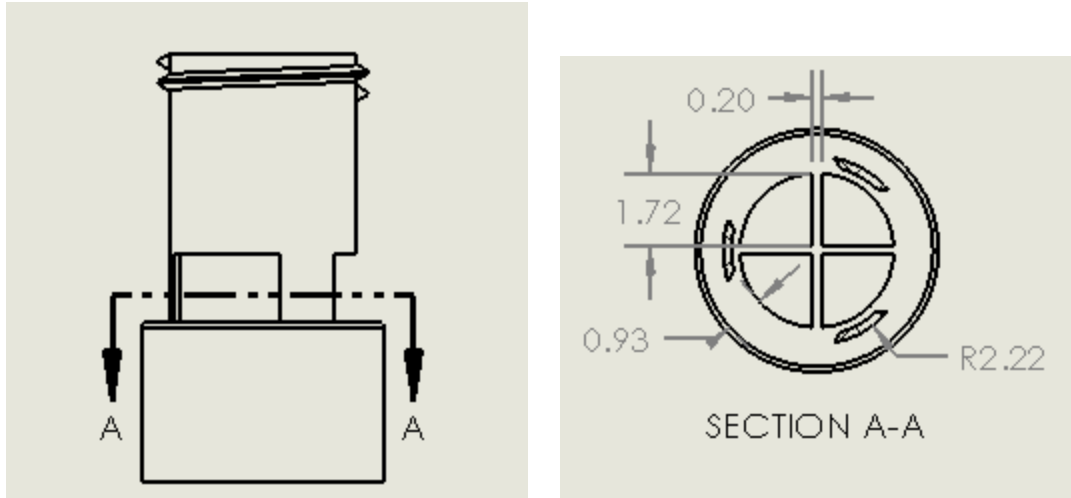
4. EETYPEEP Cap



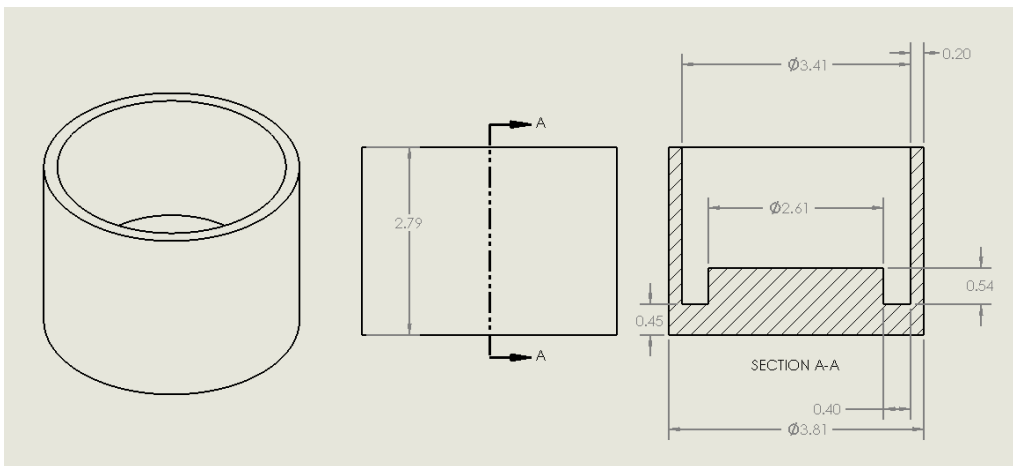


5. EETYPEEP Main Body

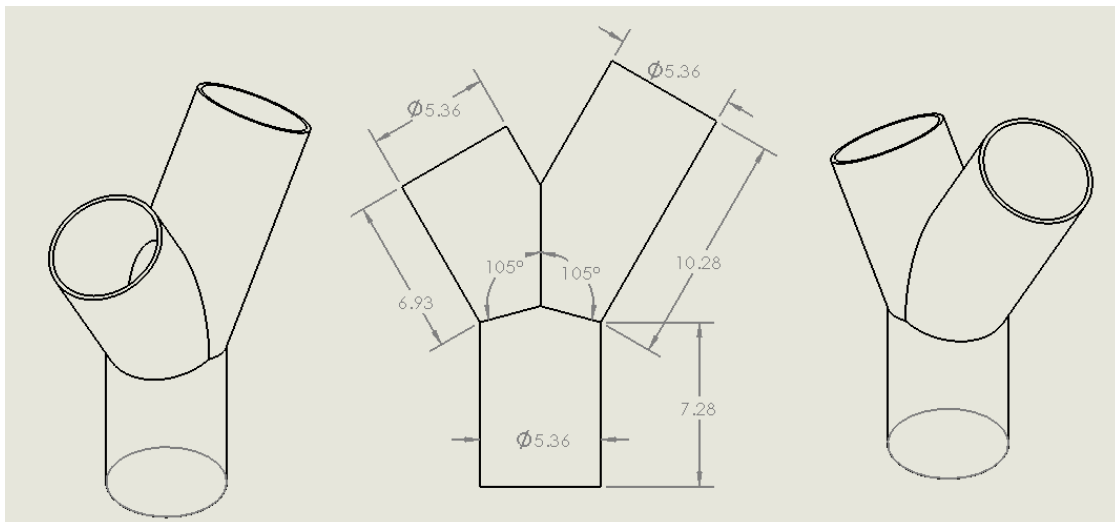


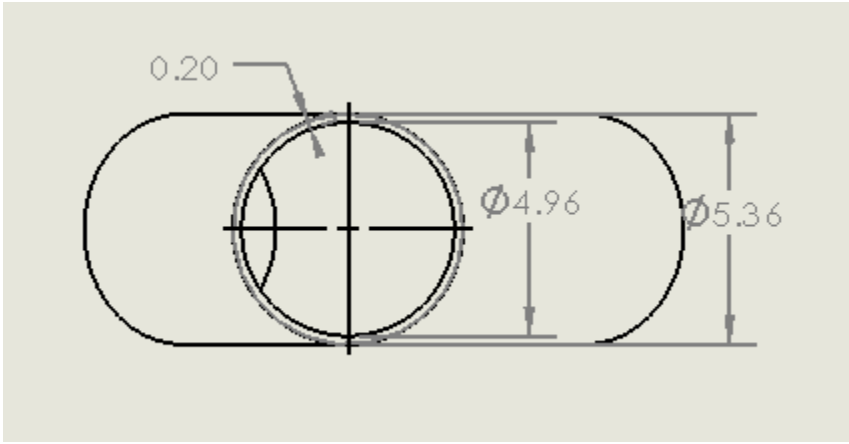


6. Expiratory Outlet Diaphragm



7. Y-Piece





Appendix B: *TheSpringStore.com Order*

Screenshot of compression spring specifications

PC051-1266-6500-SST-2021-C-N-IN

Don't see what you're looking for? [Modify your search](#) or send us a [quick quote](#)

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Note: Above image is for defining measurements of spring (reference only) and is not an image of your spring.

Compression Spring Dimensions - IN	
Stock Part Number	PC051-1266-6500-SST-2021-C-N-IN
Outer Diameter	1.266
Inner Diameter	1.164
Free Length	2.021
Solid Height	0.382
Wire Diameter	0.051
Total Coils	6.500
Rate (lbs./in.)	1.042
Max. Load	1.708
Max. Deflection (Max. Travel)	1.639
Material Type	SST - Stainless Steel 302
End Type	C

PC051-1266-6500-SST-2021-C-N-IN

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\$5.120

IN STOCK

Min. order amount is \$40 USD can be met with different spring products

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Appendix C: Sections from Perfect Prime Digital Pressure Gauge AR168 Instruction Manual



1. PRODUCT INTRODUCTION 2. BASIC FUNCTIONS

PRODUCT INTRODUCTION

The AR168 is a professional high precision, high range, high resolution digital pressure gauge for indoor temperature measurement with a large screen display. It measures the pre-blue detection pressure value relative to the current atmospheric pressure. The dual channel can simultaneously detect the pressure difference between two detection ports. The product is widely used in natural gas pipelines, air-conditioning refrigeration and ventilation systems, mechanical hydraulics, plastic molding, bio pharmaceutical molding, mining area pressure detection, gas, liquid and production industrial equipment pressure detection.

BASIC FUNCTIONS

1. °C/°F display
2. Pressure value display
3. °C/°F Conversion
4. Hold data mode
5. Data storage function
6. Data search function
7. Maximum/minimum data mode
8. Automatic shutdown function



3. TECHNICAL PERFORMANCE

Measuring Range	±2.999 Psi
Unit of measurement	Psi, kg/cm2, ozin2, bar, mbar, Pa, kPa, inHg, mmHg, inH2O, ftH2O, cmH2O
Accuracy	±0.3% FSO (25°C)
Repeatability	±0.2% (MAX ±0.5% FSO)
Linearity/Hysteresis	±0.29% FSO (25°C)
Measurement rate	0.5s
Data Storage	100 groups
Maximum withstand pressure	50KPa
Automatic shutdown conditions	No operation for 15 mins
Positive pressure range display	Err0
Over negative pressure range display	Err1
Working Temperature	0-50°C (32-122°F)
Working Power	9V battery
Physical dimension	164 x 70 x 32 mm
Weight	200g



4. RANGE OF PRESSURE MEASUREMENT

Unit	Range	Resolution
kPa	±20.68	0.001
psi	±2.999	0.001
kgcm ²	±0.210	0.001
ozin ²	±47.99	0.01
bar	±0.206	0.001
mbar	±206.8	0.1
inHg	±6.106	0.001
mmHg	±151.1	0.1
inH ₂ O	±83.02	0.01
ftH ₂ O	±6.918	0.001
cmH ₂ O	±210.8	0.1
Pa	±9999	1



5. SYMBOL DEFINITION & BUTTON LOCATION



- | | |
|-----------------------|------------------------------|
| ① Temperature Display | ⑤ Differential Pressure Mode |
| ② Low Power Symbol | ⑥ Reading display |
| ③ Hold Function | ⑦ Pressure Units |
| ④ Max/Min Reading | |

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