Thermodynamics and the Heart

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Project #2

Due: 12-01-2013
Introduction

From a mechanical standpoint, the heart is probably the easiest to describe since it is for the most part a pump. Using negative and positive pressures within its interiors, it is able to fill with blood and push that blood throughout the body. Because of this mechanical view, it would be interesting to view the heart through an engineering standpoint, gain a perspective as to how the heart works and see if there is any thermodynamic concept we can learn from this experience. This is what Eduardo Cesarman and Norman Brachfeld did in 1977 when they wrote their article “Thermodynamics of the Myocardial Cell.” They took the understanding of the physiology of a myocardial cell and applied some thermodynamic principles to help in understanding the nomenclature of the cardiac cycle. However, in order to really delve into what their article is arguing, we must first examine the heart’s physiology and understand how the heart cycle works, second learn about signaling on the cell membrane, and then finally see if we can demonstrate some thermodynamic principles through the heart’s functions.

The Heart

The primary function of the heart, as stated above, is to pump blood throughout the body. We can view this process in two phases: a mechanical contraction phase (systole) and a mechanical relaxing phase (diastole). Briefly, what happens in the cardiac cycle is that the heart will receive an action potential that will tell it to contract. The heart muscles will squeeze in on themselves and push the blood within the heart through the rest of the body. When the muscles relax, the interior volume of the heart will increase again, creating negative pressure and will pull in blood from the venous side of the circulatory system. The cycle will continue again, and we have blood pumping through the body.

![Anatomy of the heart at diastole and systole](Villarreal2006)

Figure 1. Anatomy of the heart at diastole and systole (Villarreal 2006)
Physiologically, how the heart functions is more complicated than this, especially in the cellular level. In order for a muscle contraction to happen, we need to first stimulate the muscle through the propagation of an action potential through specialized conducting tissues within the heart. The cell membrane is created by a lipid bilayer that separates the interior and exterior of the cell. Through different channels that are located on this membrane, the composition of the intracellular fluid and the extracellular fluid changes among each other. One kind of channel is called an active transport and is so called because of its need of an input of energy through ATP in order to move ions up their concentration gradient across the membrane. The end result of the active transport’s job is an electrochemical gradient of an ion about the cell membrane that is now polarized, as can be seen in [Figure 2]. (Costanzo 2006)

![Figure 2. Active Transport with Ion Gradients (Connexions 2013)](image)

Another channel through the membrane is called passive transport. When this channel is open, it allows for the ions to move down their electrochemical gradient. This in turn depolarizes the membrane and equalizes the concentrations of the ions on both sides. It is through this depolarization that signals are sent to electrically activate the heart. The depolarization from that channel will spread along the membrane and in turn activating other channels to open and depolarize the membrane as well. This will propagate until the signal reaches a part of the myocardial cell called the T-Tubule. The T-Tubule then allows for an inward current of Ca\(^{2+}\) ions to come into the cell and triggers release of additional calcium ions to be released from the sarcoplasmic reticulum. It is this increase of calcium that begins the contraction of the cardiac cell. (Costanzo 2006)

**Application of Second Law of Thermodynamics**
Now that we know the basics of cardiac physiology, we can look at two thermodynamic concepts that can be demonstrated through what we have learned. First, we look toward the second law of thermodynamics. In lecture, we discussed how energy has a direction and a quality, and there is no difference when we look in physiology. The Clausius Statement for the second law states that “it is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a lower-temperature body to a higher-temperature body.” (Cengel 2011) This should apply the same with ion concentration.

Chemistry teaches us that particles like to diffuse from areas of high concentration to areas of low concentration until a solution is uniform. In the same way, the ions that inside and outside of cells (if able to) have a tendency to diffuse from areas of high concentration to areas of low concentration. In order to move an ion from a low concentration to a high concentration, we must put in energy to the system. In this case, that energy comes in the form of a high level phosphate, or ATP. This demonstrates that even complicated processes in our bodies’ physiology follow the second law of thermodynamics.

Cesarman and Brachfeld argue that “the heart may be show to be thermodynamically active during mechanical relaxation (the ‘resting’ state) and thermodynamically passive during mechanical contraction (the ‘active’ state).” This is due to different perspectives they take on the cardiac cycle. When referring to mechanical contraction, the passive channels are opening, allowing ions to flow down their concentration gradient. We are not putting any extra energy into the system. We are allowing that potential diffusion energy help potentiate the contraction of the heart. On the other hand, when the heart is relaxing, the active transports are reforming the membrane potentials and thus putting in energy. This is why the authors claim that at diastole, the system would be thermodynamically active. (Cesarman and Brachfeld 1997)

**Mechanical Efficiency of the Heart**

The second concept that we can look at with the heart and its physiology is the idea of efficiency. If we view the heart as a machine or pump, we can actually imagine qualitatively that it has an efficiency that can be stated as follows:

$$\mu_{heart} = \frac{W_{out}}{W_{in}}$$  \hspace{1cm} (1)

where $W_{out}$ is the work the heart puts out through pumping blood through the body and $W_{in}$ is the metabolic energy required to make the heart contract. Although the values of $W_{in}$ and $W_{out}$ are difficult to quantify, changing their values will demonstrate changes in the heart’s efficiency. For instance, if we increase peripheral resistance (ie. Cause the arteries, arterioles, and capillaries to constrict), two things could happen: cardiac output would decrease or the
heart would use more energy to keep cardiac output constant. Either way, we would see a decrease in the heart’s efficiency. On the other hand, if pharmacologically we give a person digoxin, there will be an increase of intracellular Ca\(^{2+}\) which leads to an increase in cardiac contractility (stronger heart contractions). (Rang et al. 2004) The heart would utilize the same amount of metabolic energy, but \(W_{\text{out}}\) would increase, which in turn would increase cardiac efficiency.

These efficiencies are important because they can relate to pathology in the heart. Very low efficient hearts could mean that we are inputting a lot of energy, but the heart output would be so low that it cannot supply enough blood for the rest of the body. The heart muscles would enlarge in an attempt to increase this output, but this would only be a temporary fix since larger muscles require more energy. Eventually, the muscles will grow so large that harder contractions would stop outputting more blood, and there would be pooling of blood in the venous side of the system. Pathologically, this is called congestive heart failure. (Goljan 2010)

**Conclusion**

Thermodynamics is a prominent topic when looking at any engineering field, but that does not make its laws and concepts exclusive. Through today’s discussion, we see that these concepts are readily seen and can be applied in other fields such as medicine and biology. By looking at these other academic areas in different perspectives, we are able to understand with more depth the subject matter as well as see that these fields can be combined and applied to one another for further research and development.
Work Cited


