Diamagnetic Solutions Show a Significant Reduction in Flow Rate when Exposed to a Magnetic Field Greater than or equal to 0.7 Tesla

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Summary

Magnetohydrodynamics describes the complex interactions between water and magnetic fields. These interactions are relatively small in magnitude, and difficult to measure. However, the magnet-water interactions can be seen through the change in certain behaviors of water, such as the flow rate. This project was designed to determine the relationship between magnetic fields and flow rate in diamagnetic fluids. The researchers used a vertical 50 mL burette with a 0.7 Tesla permanent magnet attached with a clamp. Trials were run by allowing gravity to pull 25 and 50 mL volumes of water, varying concentrations of sodium chloride solution, and recording the time for the burette to empty. These trials showed that the introduction of a magnetic field led to a decrease in flow rate in all solutions, with the 1 M solution showing a significant reduction of flow rate when exposed to a magnetic field. These results led the researchers to believe that the Lorentz force opposes flow rate in a diamagnetic, electrically conductive material by a significant margin. If this conclusion is true for all diamagnetic, electrically conductive fluids, it can be inferred that magnetic fields could be used to resist the flow of blood, giving rise to a host of new approaches to surgery and the care of lesions and hemorrhages.

Introduction

Water is one of the most abundant substances on Earth. It is the only substance to naturally exist in all three states of matter at once, but what makes water truly unique are its “special properties.” These properties include its high surface tension and cohesion, neutral pH, high electrical resistance, high specific heat, and capacity as the “universal solvent” (1). While the existence of the special properties themselves is currently understood, there is little study of the effects of outside forces on these properties. This project aims to determine the interactions between a magnetic field and the properties of water – specifically the interaction between the changing electrical conductivity of a sodium chloride (NaCl) solution and a magnetic field – through the observance of changes in flow rate.

The special properties of water are caused by its polarity. Water consists of one oxygen atom that is bonded to two hydrogen atoms. These hydrogen atoms are separated by approximately 105 degrees, giving water a positive and negative end, called a dipole moment. These positive and negative ends form hydrogen bonds with each other to create the strong cohesion and surface tension of water (2). The hydrogen bonds also give water a high specific heat, since they make it more difficult to separate the water molecules. Water's polar nature enables it to dissolve any polar molecule; the water molecules will surround and isolate individual ions of the solute with the same hydrogen bonding force that holds water molecules together. The polar molecules of water are also affected by magnets (3, 4), creating the possibility of affecting the polar property of water with a magnetic field.

The easiest way to see a difference in the water properties is to measure the effects of a magnetic field on the flow rate of saltwater. Water is diamagnetic, which means it is repelled by a magnetic field. This is, again, due to its polar nature (1). However, when a conductive, diamagnetic material is exposed to magnetic field, the Lorentz force comes into play. This force is described by the equation:

$$F = qE + qv \times B \quad \text{(Eq 1)}$$

where F is Lorentz force, q is a point charge, E is electric force, v is the velocity of the charge, and B is the magnetic field. The Lorentz force acts perpendicular to the magnetic field and parallel to the electrical current (5). This force slows down the flow rate of the solution. There have been theoretical studies of this effect on blood flow (blood is diamagnetic and conductive), which show that the Lorentz force may be used to slow blood flow by up to 30% (6).

When considering the application to blood flow, the effects of the electrical current induced by the magnetic field must be considered. Maxwell derived an equation modeling the conductivity of a dilute suspension of spherical particles. The equation is as follows:

$$\frac{\sigma - \sigma_2}{\sigma + 2\sigma_2} = \frac{p(\sigma_1 - \sigma_2)}{\sigma_1 + 2\sigma_2} \quad \text{(Eq 2)}$$

where p is the volume fraction of the spheres, the subscripts 1 and 2 represent the particle and medium respectively, and σ represents the conductivity (7). Fricke later extended this equation to apply to different shaped particles.

The basic Maxwell-Fricke equation is:

$$\frac{\bar{\sigma}-\bar{\sigma}_2}{\bar{\sigma}+\gamma\bar{\sigma}_2} = \frac{p(\bar{\sigma}_1-\bar{\sigma}_2)}{\bar{\sigma}_1+\gamma\bar{\sigma}_2} \quad \text{(Eq 3)}$$

where γ is the shape factor (γ has a value of 2 for spheres and, 1 for cylinders). This is the model for a dilute solution of standard (spherical, cylindrical) particles. To model biological systems, the equation must be changed to model membrane-covered shapes (7). The equation for the resistivity of one membrane-covered sphere is:

$$\bar{\sigma}_1 = \frac{\bar{\sigma}_i-(2d/a)(\bar{\sigma}_i-\bar{\sigma}\iota_{sh})}{(1+d/a)(\bar{\sigma}_i+\bar{\sigma}_{sh})/\sigma_{sh}} \quad \text{(Eq 4)}$$

where the subscripts i and sh are the sphere material and sheath membrane, respectively (7).

The electrical resistivity is defined as 1/σ; the resistivity and conductivity of a suspension are linked by an inverse relationship. Fricke continued to derive the Maxwell-Fricke equation and developed the following equation modeling the bulk resistivity of normal human blood, assuming all particles are identical and contribute equally to the bulk resistivity:

$$p = p_m \frac{1+(\gamma-1)(v/100)}{1-(v/100)} \quad \text{(Eq 5)}$$

where p is the bulk resistivity, pm is the resistivity of the medium, and v is the volume percentage (8).

Researchers in the Netherlands have discovered that the conductivity of flowing blood increases as its flow velocity increases (9). From this finding, it can be inferred that the inverse is true, and that a decrease in blood flow velocity will decrease its electrical conductivity, or increase its resistivity. This could indicate that the electrical current induced by the magnetic field would be smaller than predicted in the Maxwell equations.

Maxwell's most famous equation relates a magnetic field with the induced electromotive force (emf):

$$\frac{d}{dt}\int(B)\,da = -\oint(E)\,ds$$

(Eq 6)

where E is emf, B is magnetic flux, da is a discrete length and ds is a discrete cross-sectional area. The induced emf determines the current induced. This equation does not exactly apply to diamagnetic fluids, since, unlike the Maxwell-Fricke equations [3], [4], and [5] it does not consider the effects of magnetic field on the conductivity of a fluid. Therefore, Maxwell's equation [6] must be unified with the Maxwell-Fricke equations [3], [4], and [5] in order to accurately model the effects of a magnetic field on moving, conductive, diamagnetic fluids such as blood.

The primary goal of this project is to determine the extent to which magnetic field has, if any, on the flow rate of water or salt solutions of water. From the previously stated research, it is hypothesized that flowing water, when exposed to a magnetic field, will experience forces resistive to the flow direction resulting in a decrease of flow rate. It is further hypothesized that the reduction of flow will be larger in magnitude in salt solutions of water. If these hypotheses are confirmed then it will imply that there is some change in the properties of water when exposed to magnetic field.

Results

The hypothesis of this project was that water and salt solutions would experience a reduction of flow rate when exposed to a magnetic field. To test this hypothesis, the following experiment was devised: A 50 mL burette was set up vertically, and water was run through it (Figure 1). The times for the water to flow from the 50 mL to the 25 mL mark, and from the 50 mL to the 0 mL mark were recorded with distilled water. This process was repeated for a total of ten runs each of distilled water, 0.5 M, and 1 M NaCl solutions. A magnet with a 0.7 Tesla (7000 Gauss) surface field was then placed in contact with the thinnest part of the burette, about one inch below the stopcock. The flow rate trials were run again, and flow times recorded for a grand total of 60 trials. The temperature of the room was also recorded for each trial.

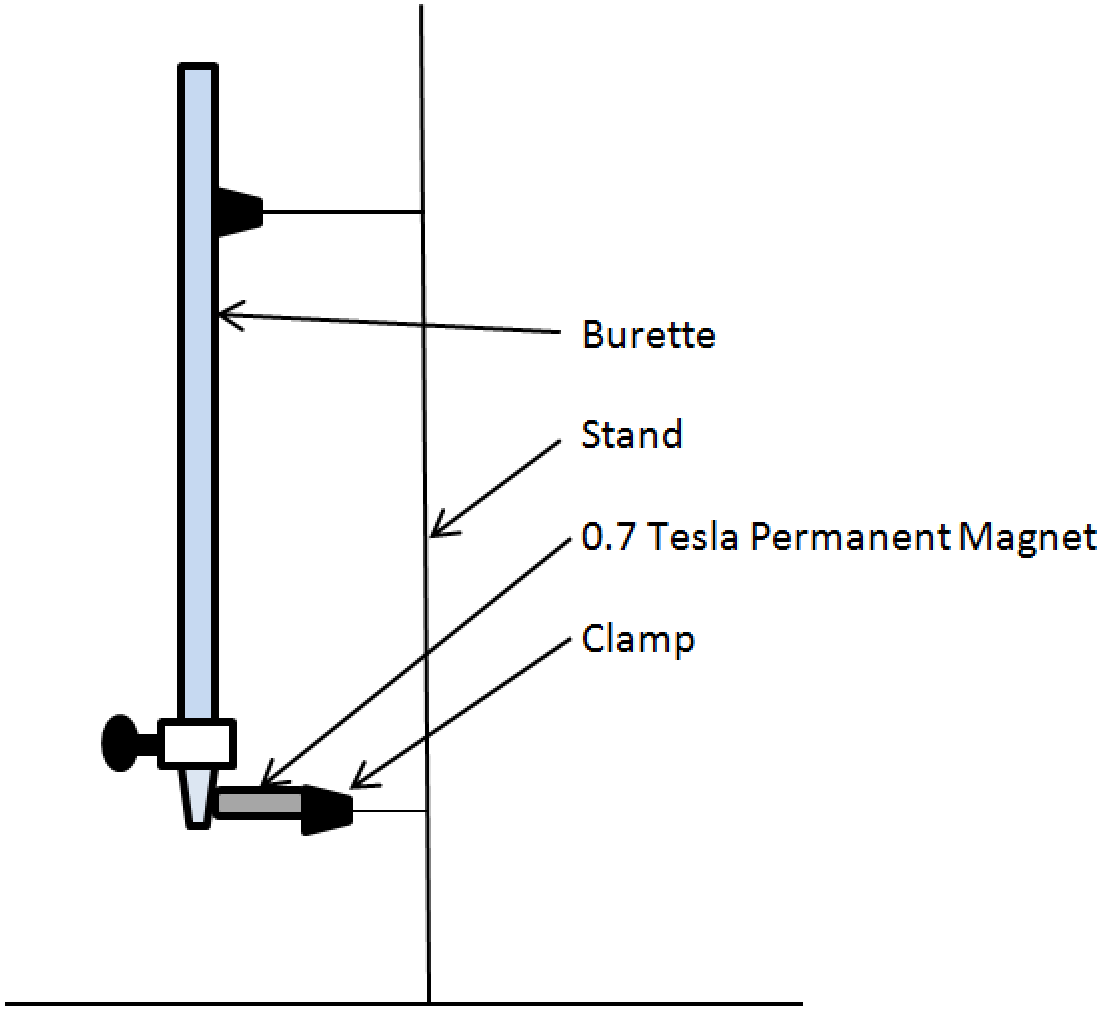

Figure 1: Experimental set-up. This figure shows a schematic depicting the position of the magnet in relation to the burette.

In all cases, there was a reduction of flow rate with exposure of diamagnetic fluids to the magnetic field. It can be seen in Table 1 that the average difference in time of flow of distilled water in the 25-mL trials was just under one third of a second, and the difference in time of flow of distilled water in the 50-mL trials was almost 0.6 seconds. While this difference seems small, the only force introduced was a magnetic field, and all reduction of flow times was due to diamagnetic interactions, which are very weak. As shown in Table 2, the 50-mL 0.5 M NaCl trials, flow times were reduced by an additional 0.1 to 0.2 seconds. This is with a small ratio of Na+ and Cl- ions present in the solution. When the ion concentrations were doubled, the flow times in the 50-mL trials were further reduced by an average of 1.75 seconds, as seen in Table 3.

Trial	Distilled - 25 mL		Distilled - 50 mL	
	Magnet Off	Magnet On	Magnet Off	Magnet On
1	25.28	25.88	65.35	65.47
2	25.25	25.56	65.47	65.78
3	25.13	25.35	64.65	65.31
4	25.22	25.34	64.56	65.89
5	25.19	25.63	64.65	65.97
Average - Day 1	25.214	25.552	64.936	65.684
6	25.19	25.39	66.2	66.62
7	24.96	25.25	65.84	66.28
8	25.18	25.33	66.12	66.31
9	24.99	25.27	65.79	66.39
10	24.93	25.36	65.7	66.53
Average - Day 2	25.05	25.32	65.433	66.055

Table 1: Distilled water trials. This table shows the flow times of the 25 mL and 50 mL trials of the distilled water trials, both with and without magnetic field.

Trial	0.5M NaCl - 25 mL		0.5M NaCl - 50 mL	
	Magnet Off	Magnet On	Magnet Off	Magnet On
1	25.37	25.73	64.4	65.6
2	25.28	25.81	64.8	65.33
3	25.29	25.64	64.3	65.33
4	25.41	25.88	64.7	65.35
5	25.18	25.57	64.8	65.51
Average - Day 1	25.306	25.726	64.6	65.424
6	25.52	25.91	66.27	66.73
7	25.55	25.92	66.28	66.95
8	25.52	25.85	65.97	66.83
9	25.58	25.82	66.22	66.79
10	25.52	25.89	65.88	66.71
Average - Day 2	25.538	25.878	65.362	66.113

Table 2: 0.5 M NaCl solution trials. This table shows the flow times of the 25 mL and 50 mL trials of the 0.5 M NaCl solution trials, both with and without magnetic field.

Trial	1M NaCl - 25 mL		1M NaCl - 50 mL	
	Magnet Off	Magnet On	Magnet Off	Magnet On
1	25.72	25.97	65.81	67.96
2	25.53	26.19	66.22	68.22
3	25.66	26.16	66.19	68.41
4	25.69	26.27	66.31	67.83
5	25.38	26.3	66.35	67.95
Average - Day 1	25.596	26.178	66.176	68.074
6	25.68	26.18	66.31	68.25
7	25.65	26.23	66.41	68.38
8	25.52	25.97	66.41	68.17
9	25.52	25.93	66.19	68.28
10	25.8	25.93	66.5	68.31
Average - Day 2	25.634	26.048	66.27	68.176

Table 3: 1 M NaCl solution trials. This table shows the flow times of the 25 mL and 50 mL trials of the 1 M NaCl solution trials, both with and without magnetic field.

After running a multi-factorial ANOVA test and a Tukey test, the 1 M trials showed a statistically significant difference from the distilled water trials. The ANOVA test showed that the critical F values for a null hypothesis (that the changed variable did not create a difference in bell curves) for the magnetic field change and NaCl concentration change, were 3.17 and 4.02 respectively. Additionally, the critical F value for the interaction null hypothesis (there is no interaction between magnetic field and NaCl concentration) was 3.17. The F values for the null hypotheses were 46.831 for magnetic field and 57.293 for the NaCl concentration; therefore both null hypotheses had to be rejected. The F value for the interaction null hypothesis was 7.9912, so that hypothesis must also be rejected. The Tukey test was run with the distilled water and no magnetic field as the baseline and designated as case 1, distilled water with magnetic field designated as case 2, 0.5 M NaCl solution and no magnetic field designated as case 3, 0.5 M NaCl solution with magnetic field designated as case 3, 1 M NaCl solution and no magnetic field designated as case 5, and 1 M NaCl solution with magnetic field designated as case 6. When comparing the cases the p values were 0.07722 between cases 1 and 2, 0.7269 between cases 1 and 3, 0.0615 between cases 1 and 4, 0.0419 between cases 1 and 5, and 0.0041 between cases 1 and 6. The threshold for significance is a p value below 0.05 meaning the only significant differences were between cases 5 and 1 and cases 6 and 1. These were both of the 1 M trials, with the no magnetic field trial just crossing the threshold of significance and the magnetic field trial being very significant. None of the other trials had p values below 0.05 and were therefore not significant.

Figure 2 shows the change in flow rate due to magnetic field of all three concentrations. The average flow rate reduction of the distilled water, 0.5 M NaCl solution and 1 M NaCl solution with the magnetic field all showed a reduction of flow rate. The trend is that as salt concentration increases, percent reduction of flow rate increases. There are some outliers, but they can be attributed to the fact that trials with and without magnetic field cannot be run simultaneously. The temperature of each trial is shown in Figure 3. The results in Figure 3 support the conclusion that the variance in temperature yielded an insignificant change in flow rate reduction.

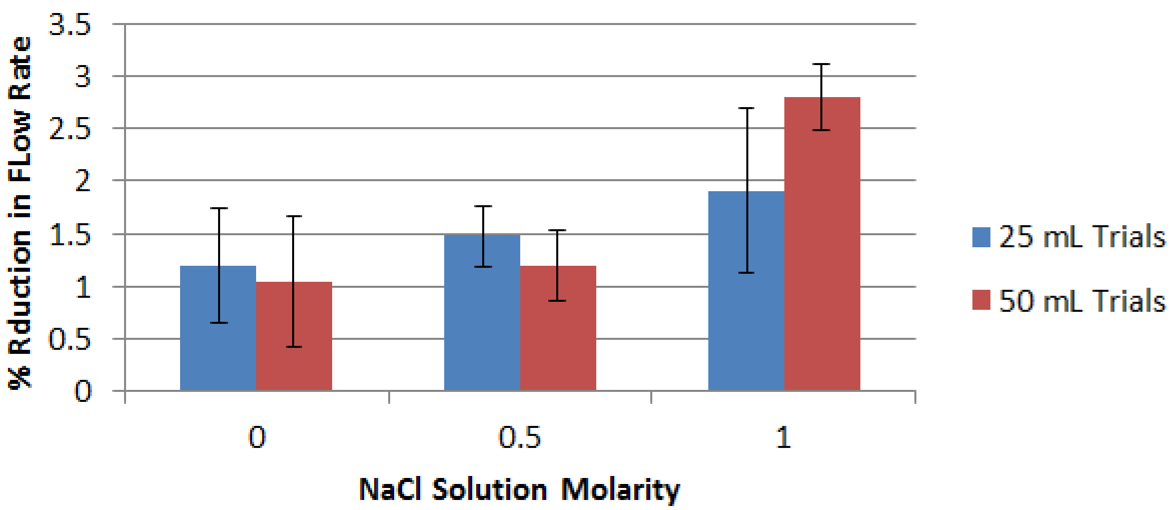

Figure 2: Change in flow rate due to introduction of a magnetic field. This figure shows the average reduction of flow due to the magnetic flow across 10 trials. The reduction value is the difference in flow rate of the magnetic and non-magnetic trials as a percentage of the non-magnet run. Error bars represent the standard deviation of 10 trials.

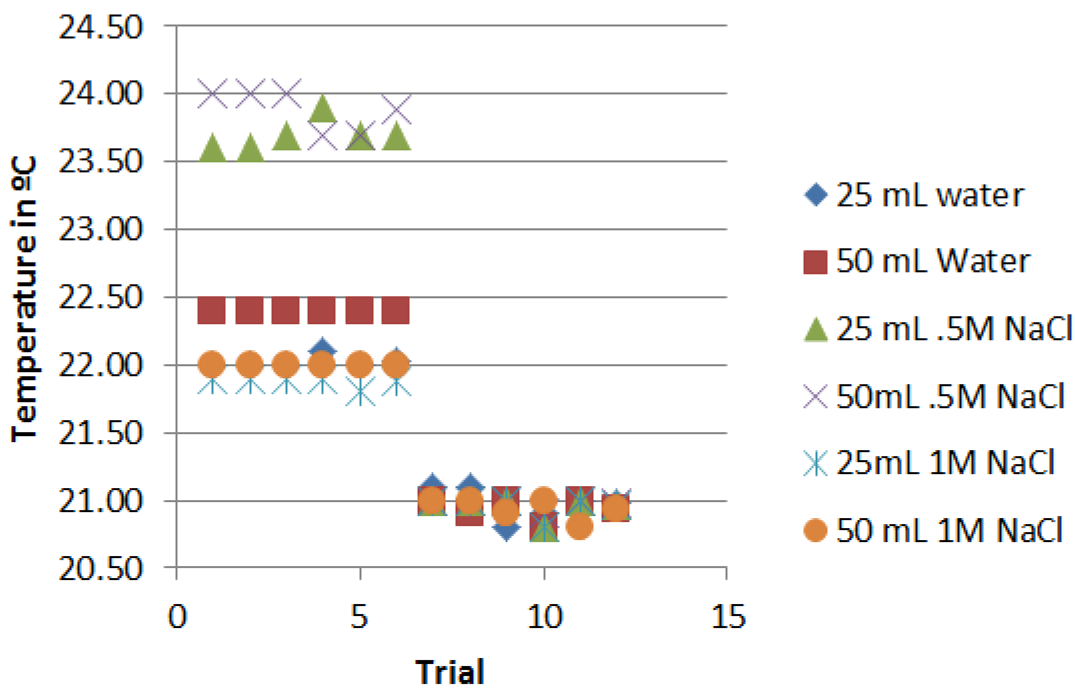

Figure 3: Ambient Temperature during trials. This figure shows the temperature of the room during each trial. The temperature has a very minor impact on the flow rate because water expands slightly as temperature increases.

Discussion

The goal of this project was to observe any changes in the flow rate of water and salt solutions thereof when exposed to a magnetic field. The hypothesis was that there would be a reduction of flow rate in all cases, with a larger reduction in solutions with higher NaCl concentration. This hypothesis was tested by making three samples and running them through a burette while recording the time of flow. The samples consisted of distilled water, a 0.5 M NaCl solution, and a 1 M NaCl solution. These trials were run with no magnetic field and in the presence of a 0.7 Tesla magnetic field. There was a reduction of flow time, and therefore flow rate, in all of the trials with the most reduction of flow in the 1 M NaCl solution and the least reduction of flow in the distilled water trials.

The reduction in flow rate may be explained by several methods. For the 25-mL sample, the temperature likely reduced the flow rate, but by a miniscule margin. The differences in coefficients of thermal expansion of water at the measured temperatures are approximately 0.000214 cubic centimeters per degree Celsius. When entered into the equation for the thermal expansion of water, the difference in coefficients yields a negligible difference.

The more likely reason for the difference in flow rate is the diamagnetic repulsion from the magnet. This repulsion would increase the friction between the water and the burette, resulting in a force opposing the flow rate. Conservation of energy explains the larger difference in flow rate in the 50 – mL trial. The 50 – mL trial shows more then twice the flow rate difference. As the water drains, the center of mass of the water moves closer to zero and the mass decreases. These are two of the three variables that determine gravitational potential energy, the third being gravity itself. By setting the potential energy ($U = mgh$) equal to kinetic energy, modeled by the equation- $K = (1/2)mv^2$, one sees that velocity (v) will decrease with the change in energy, K, expected in the trials.

An explanation of the differences in flow rate in the 0.5 and 1 M NaCl solutions takes further analysis. In the 1 M 50-mL trials, the change in flow rate was 60% higher than that of the change in distilled water. This difference means that the magnetic field must have played a major role by inducing current and therefore, the Lorentz force. When a magnetic field is applied to a moving, conductive object, an electrical current is induced and, in a flowing liquid, it produces a force that resists the flow. Distilled water is not conductive. However, when NaCl is introduced into the water, the water breaks the salt into two ions, Na^+ and Cl^-. These ions make the solution electrically conductive, allowing the Lorentz force to oppose the flow. The 0.5 M NaCl solution trials showed a change in flow rate more than that of water, but less than that of the 1 M NaCl solution. This is generally what was expected, although the flow rate reduction in the 50-mL trial was less than expected, and the reduction in the 25-mL trial was more than expected. The flow rates in the non-magnetic runs still show a small difference which is explained by the differences in density of the NaCl solutions and water. The error from the different densities was eliminated from skewing the results by measuring the change in flow rate instead of using only the times of flow rate.

There were three probable sources of error in this project. The first is the reaction time of the researcher. This variance has been shown in studies to average between 0.2 and 0.3 seconds for the average human (12) which means that the trial times could be plus or minus 0.3 seconds. While variance could result in only slight difference in flow rate for the 25 mL trials, it could double the difference in flow rate between trials. Nevertheless, even when this error is factored into the trials, the difference in flow of the 1 M NaCl solution is still greater than that of water. A motion sensor and a computer program could be used to drastically reduce this error and this set-up is recommended for any future studies. Another possible source of error is contamination of the solutions changing the conductivity, and therefore flow rate of the solutions. The internal error of contaminants (if there were any) is eliminated by using the same samples for all of the trials. The effect of the contaminants could be significant if the contaminants interacted with the magnetic field in any significant manner. The best way to deal with this is to test the samples before and after the trials for substance that could have interacted with the magnetic field and take those substances into account when determining the cause of the flow rate change. The third source of error is that the 0.5 M sample became contaminated, so a 2 M sample was diluted to 0.5 M for use in this experiment. If this dilution were done imprecisely, the concentration of the solution could be greater or less than the expected 0.5 M. No trials were run with the contaminated solution.

Although more research is necessary to fully confirm our results, it can be tentatively concluded that magnetic fields affects the properties of water. This change in properties could be used in a variety of ways, from increasing the cohesion of water droplets to reduce water loss, to increasing the adhesive properties of water to make a water-based alternative to adhesive tapes or glues. Understanding these property changes is also crucial if diamagnetic levitation is to be utilized, because the diamagnetic levitation of water uses eight Tesla magnetic fields, which could easily change the properties of the levitated water in a drastic way.

The second promising area of application is in the medical field. If the sodium chloride is used as a crude analog for human blood, then it is possible to use a magnetic field in lieu of tourniquets or anticoagulants in surgeries and emergency care. The reduction in flow rate was only about 2% in the 1 M trials, but that was with a relatively weak magnetic field. The largest magnetic pulse ever recorded was almost 98 Tesla, and the standard MRI machine uses about a three Tesla magnetic field, with experimental models using up to eight Tesla. With fields of this strength, blood flow could be reduced by a drastic margin.

The largest potential problem in this application is that a magnetic field will induce an electrical current opposite to the initial magnetic flux as shown in Faraday's Law of Induction and Lenz's Law. These laws were originally applied to wire coils, but also apply to any conductive material moving through a magnetic field, including diamagnetic solutions and suspensions such as blood. To determine the magnitude of this induced current, we must consider the Maxwell-Fricke Theory. The Maxwell-Fricke Theory models the electrical conductivity of dilute suspensions. It states that the conductivity of individual particles depends on the conductivity of the material of the suspended particle, the resistivity of the medium, the shape of the suspended particles, and the resistivity and thickness of any membrane covering the suspended particles [4]. To compensate for the ellipsoidal nature of blood cells, the equation [5] was derived by Fricke to model the resistivity of blood as a whole (the previous equation models the resistivity of one red blood cell). This supports the finding that blood conductivity increases with increased flow rate, and conversely, decreases with decreased flow rate (9).

The Maxwell-Fricke Theory yields the idea that as the blood flow rate is reduced, the resistivity of the blood will increase, reducing the induced electrical current. In addition to this reduction, one other concept must be considered. Red blood cells are rich in iron, a ferromagnetic material. A magnetic field will cause the red blood cells to start to align and, in conjunction with the reduction of shear forces of the blood vessel walls due to a reduction of blood flow velocity, will make the red blood cells more effective as a whole at resisting electrical current. Imagine each red blood cell as a resistor arranged in a parallel circuit. The magnetism and reduction of flow velocity will start to shift the cells, so that they resemble more of a series circuit, greatly increasing the collective resistivity. The greater resistivity means that a stronger magnetic field can be used perpendicular to the blood vessel because of the reduced electrical current. This increased field will in turn further increase resistivity, reducing the electrical current. This reduction in current cannot continue to infinity because the magnitude of the magnetic field is greater than that of the change in resistivity, but it still means that stronger magnetic fields than originally expected can be used.

Another consideration in this application is that blood has a far greater number of ions than at much lower concentrations than the NaCl solution analog. To fully understand the effects of magnetic fields on blood flow, more trials in this field must use ion concentrations more similar to blood. Furthermore, blood acts much more like a suspension than as a solution and so a better analog to blood would be a suspension of diamagnetic particles in a mixed ion solution.

In conclusion, the interactions between electrically conductive diamagnetic fluids and magnetic fields are far more complex than meets the eye. By observing the changes in flow rate in the presence of a magnetic field, and comparing it to what is predicted by equations that omit that field, the reduction of flow rate due to the Lorentz force, can be more easily observed. Once fluid-magnet interactions are understood and modeled in equations, they can be exploited and used to great effect, especially in the medical field.

Materials and Methods

First, a 50 -mL burette assembly was put together as shown in Figure 1. Then, 52 mL of distilled water were added to the burette, and the temperature of the room was recorded. The stopcock was then opened completely, and the times for the burette to empty from the 50 mL mark to the 25- and 0- mL mark were recorded. This process was repeated ten times with distilled water. A magnet (with a pull force of 18 pounds and a surface field of 0.7 Tesla) was then placed next to the thinnest part of the burette, (just below the stopcock as seen in Figure 1), and the temperature was recorded.

Ten more trials were run (the first five were done on one day, and the second five were done at a later date with a lower room temperature) recording any changes in the observed flow (bubbles, etc.), as well as time. A 1 M NaCl solution was then made by adding 11.68 grams of NaCl to 200 mL of distilled water, and the process of measuring flow rate was repeated with and without the magnet. The above process was repeated again, and the percentage change in flow rate was calculated. After the two solutions (0 M and 1 M) were tested and the results analyzed, one more solution was made with a molarity of 0.5 by diluting a pre-made 2 M NaCl solution. The same procedure was followed with and without the magnet, and the data recorded. The data are shown in Tables 1, 2, and 3. Figure 2 shows the percent reduction of flow rate for the trials.

Two variables were manipulated in this project. The first was the conductivity of the liquid. This was controlled using samples from three solutions with different but constant conductivities. The second manipulated variable was the magnetic field. This was controlled using one magnet, which was either present or absent, acting as an on/off switch for the magnetic field. The field was thus either nonexistent or present.

After obtaining the data, a multi-factorial ANOVA test was run to determine if magnetic field and/or NaCl concentration had a significant effect on the flow rate of the sample. The ANOVA works by using all of the data points to create a "bell curve" of the distribution of points and then comparing the curves to see if there is a significant difference between them. While the multi-factorial ANOVA test reveals if there is a difference between the "bell curves", it does not reveal where the difference is. A Tukey test was needed to determine where the difference occurs within the data. The Tukey test compared each bell curve formed by the multi-factorial ANOVA against the distilled water curve.

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