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Improving methods to estimate time of death from body temperature

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ABSTRACT

IMPROVING METHODS TO ESTIMATE TIME OF DEATH FROM BODY TEMPERATURE

by
Carly Berdan

By protocol, ambient and body temperatures are collected at every investigated death scene. These data has been used since 1839 to estimate the time of death, a crucial factor when it comes to cases of unnatural deaths and homicides. The Glaister Equation and Henssge's nomogram, commonly used to calculate estimated time of death, are inconsistent and often do not agree with each other. Therefore, my objective was to evaluate and improve them.

I collected data in the field and consistently measured temperature data. Furthermore, I was granted access to a database of every death in New Jersey and published data. I found that the Glaister Equation with a cooling rate of 2 degrees/hour was the most accurate available method. Moreover, I demonstrate that it is possible to develop an equation that gives a more consistently accurate time of death estimation for this data set.

IMPROVING METHODS TO ESTIMATE TIME OF DEATH FROM BODY TEMPERATURE

by
Carly Berdan

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APPROVAL PAGE

IMPROVING METHODS TO ESTIMATE TIME OF DEATH FROM BODY TEMPERATURE

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INTRODUCTION

1.1 Objective

The objective of this thesis is to evaluate and improve current methods that determine time of death from body temperature. My ultimate goal is to determine time of death more accurately and precisely without complicating the procedure, so death cases can be resolved more quickly and simply. This will help not only Medical Examiners and Investigators, but for the families at loss as well.

1.2 Background Information

Knowing the time of death is an important factor when solving unnatural death related cases (Spitz, Spitz, & Fisher, 2006). It is important to find out not only how and why a person has passed away but also when. Moreover, the time of death can contribute to knowledge of other aspects of complete cases, especially in homicides. The postmortem interval (PMI) can be crucial in homicide cases since it can potentially convict or acquit a suspect. When determining time of death, the first and most common data collected is body temperature, measured with a thermometer under the armpit (axillary body temperature) after the body is found along with ambient temperature (Kelly, 2006).

Time of death in relation to body temperature has been extensively studied. Since postmortem body temperature can be easily and quickly obtained, the search for a formula that uses this parameter to estimate the time of death has been sought for years (Lyle, 2008). Starting in the 19th century, research began on time of death with body temperature having a relationship with its environment. Algor mortis, which is the change in the body temperature after death, is a widely known and highly utilized term in forensics. It was first introduced by Dowler in 1849, and the first data were published quickly thereafter. The body is found to cool at a specific rate until it reaches the ambient temperature. On the other hand, if the body was in an environment that was much hotter, then the change in body temperature post mortem would be positive until it matched its hotter environment. There are three important factors involved in cooling of the body which are conduction, convection, and evaporation. Each of these mechanisms can help the body lose or gain heat in their own way. These three mechanisms play a huge role in this complex process and are a reason it is so difficult to apply a simple formula for the estimation of PMI.

Despite many decades of investigation on the topic, accuracy in determination of the time of death has not significantly improved, and no single method can be reliably used to accurately estimate the PMI (Brooks 2016). The Glaister Equation is solely based on algor mortis. The equation is (98.7 degrees Fahrenheit – the body temperature) / (1.5). This equation assumes that body temperature drops about 1.5 degrees per hour. The Glaister Equation is just one example; there are a number of other equations, methods, and nomograms that convert temperature data to time of death. However, the Glaister Equation and Henssge's Nomogram (Henssge & Madea, 2004), are the two methods that are mainly used and known in forensics. Alas, because there are so many outside factors that can play a role, neither of them are consistently accurate. Outside factors include ambient temperature, body weight, any potential objects touching the body at death, and clothing which can all effect an investigation when determining a decedent's time of death. Our data confirms that algor mortis is of very limited utility in determining the postmortem interval in bodies that have been refrigerated (Wardak & Cina, 2011). With all of these components playing a role when it comes to time of death, it is obvious that the two current methods used in forensics, the Glaister Equation and Henssge's Nomogram, are not adequately accurate. Therefore, evaluating and improving these time of death estimation methods is necessary.

1.3 Procedure

To get a better understanding of the data used to determine PMI, I attended scenes with the Investigators at the Northern Regional Medical Examiner's Office that involved various types of death. I was able to collect data from homicides, suicides, accidental, and undetermined deaths. It was crucial to go to scenes where the time of death was known, in order to have a known PMI that would allow me to test the equations and nomograms results. The time of death was known at witnessed events such as collapses, drive-by shooting, car accidents, train accidents, jumps, or anything on surveillance. However, because scenes with witnesses were rare, I also collected data at scenes where time of death was not known.

On a scene, the body temperature and ambient temperature are routinely collected by Investigators, and I took over that role. I used two different thermometers every time I took a reading of both the body temperature of the decedent, and the ambient temperature. The first thermometer I used was a Grainger General Digital Plastic Pocket Thermometer, which is the thermometer that the Northern Regional Medical Examiner's Office's employees use on a daily basis (Figure 1A). The second thermometer I used was a Cole-Parmer Digi-Sense Traceable High-Accuracy Thermometer with Calibration (Figure 1C).

The purpose of using a new, second thermometer was to do a small comparison which will be discussed later in Chapter 4 (Figure 4.1).

When arriving at a scene, I would record the ambient temperature with both thermometers. I would stand relatively close to the body so I would get the most precise reading. Both thermometers are digital and therefore the numbers would either increase or decrease slowly until they reached their matching temperature. When the reading became still, I recorded each ambient temperature in my notebook.

When it was time for examination of the body, body temperature needed to be recorded. The protocol that the Investigators follow includes the body temperature being taken from under the arm pit, which is called an axillary temperature. (Figure 1B & Figure 1D). Unlike ambient temperature where I was able to use both thermometers at the same time to get readings, the body temperature procedure involved only using one at a time. I used the Grainger first, and followed with the same exact procedure for the Cole-Palmer.

The arm of the decedent must be moved in order for the thermometer to be in the best position under the arm pit. If the decedent is wearing clothing, depending on the circumstances, the shirt can be rolled up from the bottom, to gain access to the axilla. If there is enough room under the sleeve, the sleeve can be rolled up and the thermometer can be inserted from that way (Figure 1B). In other circumstances like bullet holes or stab wounds of the chest, the thermometer may have to go through the collar of the shirt to get access to the axilla without compromising any evidence.

Once the thermometer is in the axilla, I moved the decedent's arm across their body, sometimes having to break rigor mortis, in order for the thermometer to be in the arm pit tight, to gain the best reading. Again, the digital numbers either increase or decrease slowly but steadily until they reach the body's temperature. When the thermometer numbers became still, I recorded the body temperature and then released the thermometer from the axilla. The second thermometer's procedure always mimicked the first. (Figure 1D).

As mentioned earlier, to assess the accuracy of the Glaister Equation and Henssge's Nomogram for my data, the time of death had to be known. Due to time, and not enough scenes having the time of death known, I was offered access to the Northern Regional Medical Examiner's Office database. The database has information on every unnatural death that has been reported to a Medical Examiner's Office in the state of New Jersey.

I surveyed case synopses to identify ones that were witnessed (so the actual time of death is known independently and accurately) and ones that were not. Once I had enough data that were witnessed and the time of death was known, I then researched other details of the report. I noted the ambient temperature, body temperature, the type of clothing the person was wearing, body weight, and if they were found on any type of object. Combining both field work and the database collection, I was able to finalize my data. My next step was to put my data into the Glaister Equation and Henssge's Nomogram and to analyze these methods.

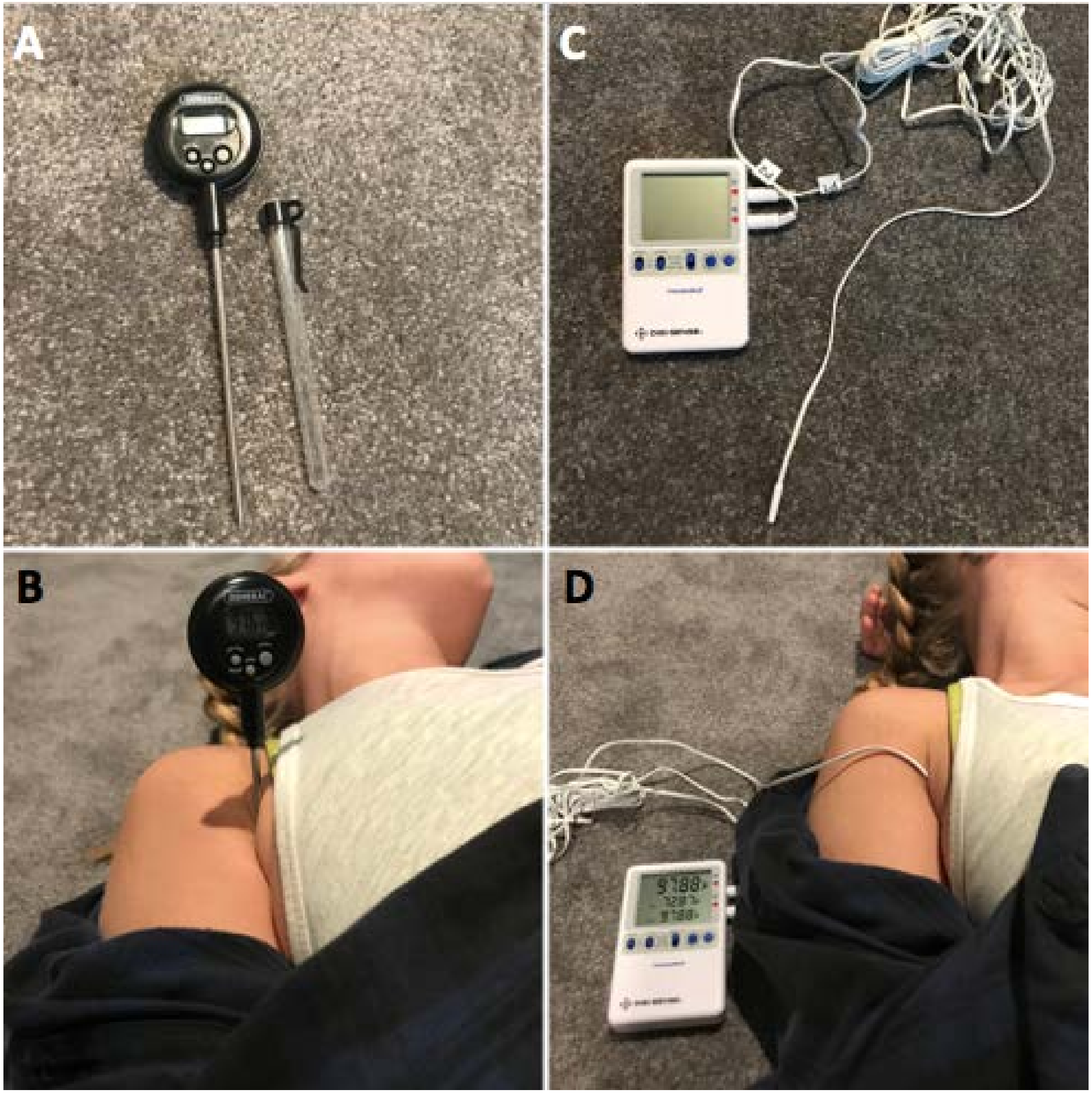

Figure 1.1 The two different thermometers are both used in a similar way. This is a live human who volunteered to be photographed. (A) Old thermometer which is currently used by the Investigators at the Northern Regional Medical Examiner's Office. It is a Grainger General Digital Plastic Pocket Thermometer. (B) A temperature is taken using the old thermometer from under the human's arm pit. (C) New thermometer that I tested to compare. It is Cole-Parmer Digi-Sense Traceable High-Accuracy Fridge/Freezer Thermometer with Calibration. (D) A temperature is taken using the new thermometer from under the human's arm pit.

CHAPTER 2

EVALUATING CURRENT METHODS

2.1 The Glaister Equation

Algor mortis, which is the cooling of the body to its environment post-mortem, was the main focus of research regarding time since death (the post-mortem interval, or PMI). The Glaister Equation calculates the hours passing after death as a linear function of the body temperature taken of the decedent. The equation is (98.7 degrees Fahrenheit – the body temperature of the decedent) / (1.5 degrees/hour) = PMI. Assumptions on the rate of body temperature drop post-mortem have varied over the years, with different values mentioned in different publications. For example, one study claimed that under average environment conditions, the clothed body will cool in air at rate of two and one-half to two degrees per hour for the first six hours and averages a loss of one and one-half to two degrees per hour for the first twelve (Simpson & Knight 1988). Another study claimed that on average, body temperature drops 1.5 degrees Fahrenheit per hour during the first 12 hours, then 1 degree Fahrenheit the next 12 to 18 hours (Spitz & Fischer, 1993). Investigator Torres from the Medical Examiner Office follows the guideline that the body can drop between 1.5 and 2 degrees Fahrenheit per hour during the first 12 hours, and then 1 degree Fahrenheit for the next 12-18 hours. According to Brooks, the Glaister Equation is the most widely used method for the estimation of PMI. Even though such methods have been in wide use in of human cases for decades, the accuracy of these methods is disappointingly low (Brooks, 2016). Knowing all of these different possibilities, led me to experiment with the Glaister Equation by trying two alternative rates.

2.2 1.5 deg/hr and 2 deg/hr Rate

With the data I collected, I wanted to assess the accuracy of the Glaister Equation. Following my mentor Investigator Torres, I decided to manipulate the Glaister Equation and use two equations for each incident. I first input my data into the regular Glaister Equation (98.7 degrees Fahrenheit – the body temperature) / (1.5deg/hr) = PMI. The results from the equation showed a majority not matching the real time of death was. The second time I input my data into the Glaister Equation but with 2deg/hr as the denominator instead of 1.5deg/hr. The new equation was (98.7 degrees Fahrenheit – the body temperature) / (2deg/hr) = PMI. The results of the equation with 2deg/hr as the denominator were definitely better than 1.5deg/hr as the denominator, but it still was not consistently good enough. With neither equation standing out significantly, I decided to look into the other popular method: Henssge's nomogram.

2.3 Henssge's Nomogram

Henssge's nomogram is still the most accurate method of measuring the time of death by means of temperature measurement (Hayman & Oxenham 2016). Henssge's nomogram is a method to determine PMI using temperature, but unlike the Glaister Equation, it also takes into consideration some other important factors. In order to use this nomogram, body temperature, ambient temperature, body weight, clothing, and whether the body was in air or water is factored into the equation.

There are two nomograms, one that is for ambient temperatures up to 23 degrees Celsius and one that is for ambient temperatures above 23 degrees Celsius (Figure 2.1).

There are two different nomograms due to the postmortem plateau. The postmortem plateau is a line that tries to represent the cooling of a human corpse which then gives the estimation of time since death. The postmortem plateau is shorter in hotter temperatures, above 23 degrees Celsius, and is longer in colder temperatures, below 23 degrees Celsius.

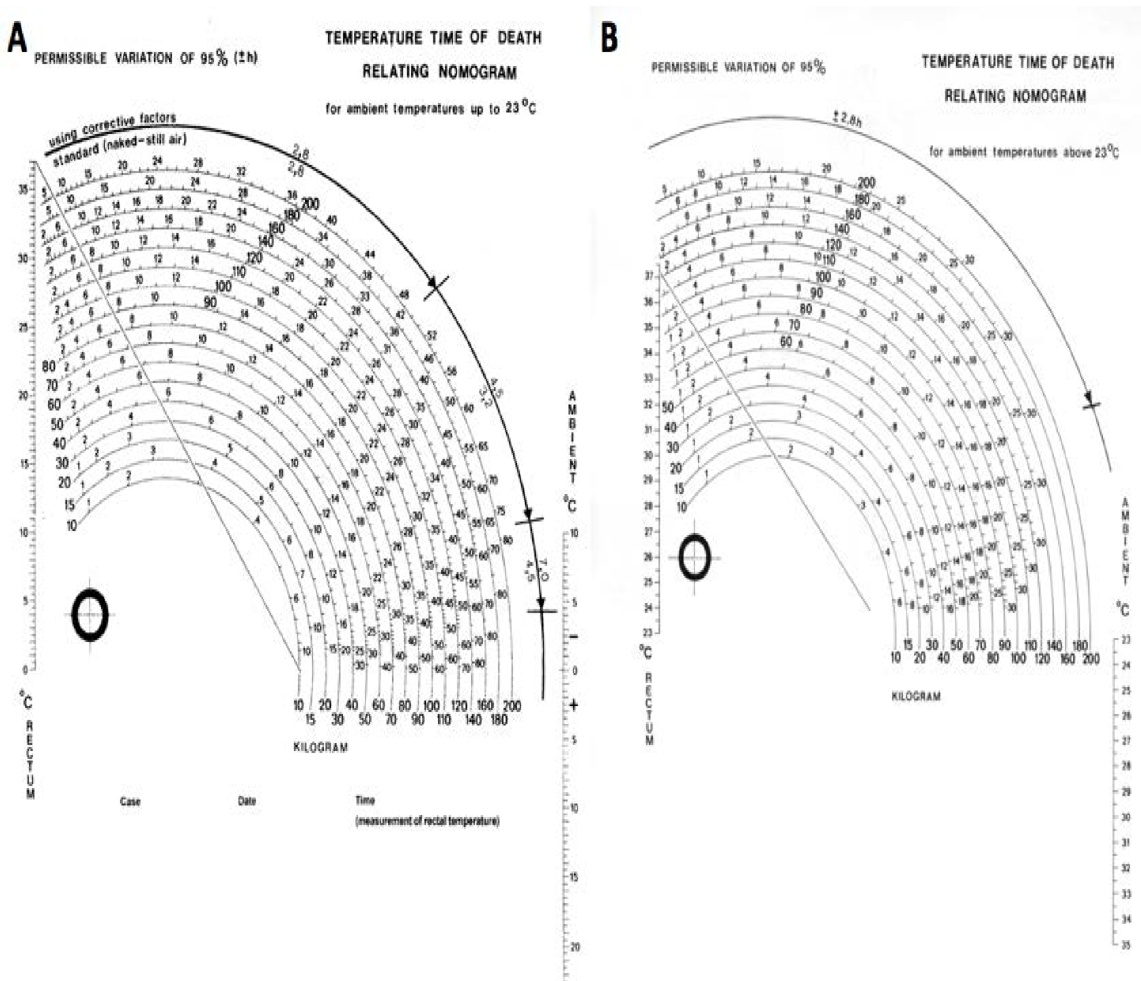

Figure 2.1 Henssge's nomogram for each situation. (A) Nomogram used for ambient temperatures up to 23 degrees Celsius. (B) Nomogram used for ambient temperatures above 23 degrees Celsius. Photo by IRIS Verona.

On the left side of the nomogram is a scale for body temperature, and on the right side of the nomogram is a scale for ambient temperature. The first step in attempting to complete this nomogram is by connecting a line that runs from the body temperature to the ambient temperature, but must cross the standard black line that is already there (Figure 2.2A). Now that there are two lines on the nomogram, (the standard black line, and the first line made by the connection of temperatures), the third line can be drawn. The third line starts from the center of the circle near the left side of the page, which has a cross through it,

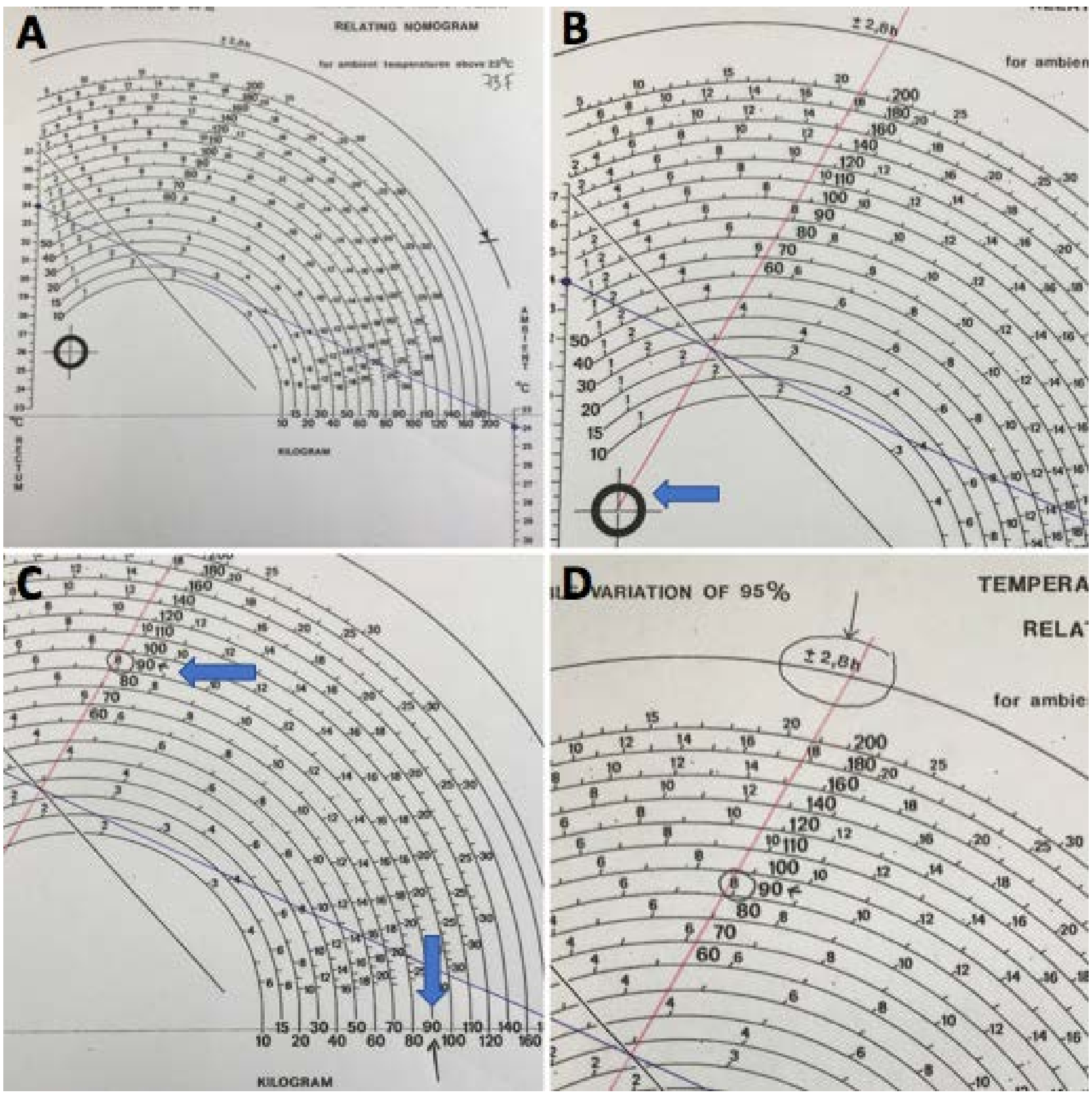

Figure 2.2 The steps to conduct Henssge's nomogram. (A) The first line is made (blue pen), the connection between the body temperature on the left scale, with the ambient

temperature on the right scale. The line must run through the standard black line that is already there. (B) The second line is made (red pen), which runs through the center circle and must go through the intersection of the black line, and first line (blue line). (C) The weight is noticed, and follows the line along it until it meets the second line (red pen). (D) The corrective factor of 2,8 must be added to the PMI found since that is the number on the outer circle where the second line (red pen) crosses.

and must cross at the intersection of where those first two lines meet (Figure 2.2B).

Following that, body weight comes into play. The weight of the

decedent is known and therefore can be seen in bold numbers, counting by tens, either on the left side of the nomogram, inner of the body temperature, or along the bottom right side, inner of the ambient temperature. If the exact body weight is not seen, then the weight must be rounded to the nearest ten. However, a corrective factor may be added to the body weight first. The chart (Figure 2.3) shows the different scenarios a decedent may be in, including different clothing situations, and therefore the corrective factor that coincides with that must be multiplied to the original body weight. That is the number that will be looked for on the nomogram. The curved line that follows the number of the new calculated body weight must be followed until it connects to where the third line that was drawn is seen (Figure 2.2C). That number will determine how many hours ago the decedent has died.

Lastly, the corrective factors are looked at one more time. That third line must be drawn out all the way to go past the outer circle line (Figure 2.2D). The outside of the circle represents if the individual was clothed and the inside of the outer circle represents if the individual was not clothed / in still air. Whether they were clothed or not, the numbers given are a plus or minus, added to how many hours ago they have died. The interval limited by the permissible variation of 95 per cent is the one and only result: the death occurred, with the probability of 95 per cent within this interval (Madea, 2015).

Utilizing the same data that I input into the two separate Glaister Equations, I constructed a nomogram for each incident.

Empiric corrective factors of the body weight

dry clothing/covering	in air	corrective factor	wet through clothing/covering wet body surface	in air / water
		.35	naked	flowing
		.5	naked	still
		.7	naked	moving
		.7	1-2 thin layers	moving
naked	moving	.75		
1-2 thin layers	moving	.9	2 or more thicker	moving
naked	still	1.0		
1-2 thin layers	still	1.1	2 thicker layers	still
2-3 thin layers		1.2	more than 2 thicker layers	still
1-2 thicker layers	moving or	1.2		
3-4 thin layers	still	1.3		
more thin/thicker layers	without influence	1.4 ...		
thick bedspread + clothing combined		1.8 ... 2.4		

Figure 2.3 The corrective factors of the body weight in Henssge's nomogram.

2.4 Analyzing the Methods

When plugging in my numbers to the Glaister Equation, I would get a result of a time of death. The output of the Glaister Equation is a single number, unlike Henssge's nomogram which gives a range. If my result from the Glaister Equation matched the real time of death known by an hour or less it was considered good, and if it matched it by a half hour or less it was considered great. As for Henssge's nomogram, because of the corrective factors, the result would be a range. Since the time of death was a range, if the actual time of death fell within that, it was considered a match. I recorded the results of each method and how they corresponded with the real time of death (Figure 2.4).

The Glaister Equation using 1.5 deg/hr as the denominator matched the actual time of death five times (Figure 2.4). The Glaister Equation using 2 deg/hr as the denominator matched the actual time of death seven times. And the third method, Henssge's nomogram matched the real time of death six times. Even with Henssge's nomogram allowing more room for error and a broader range for results, it still was not the best method that gave the most accurate results.

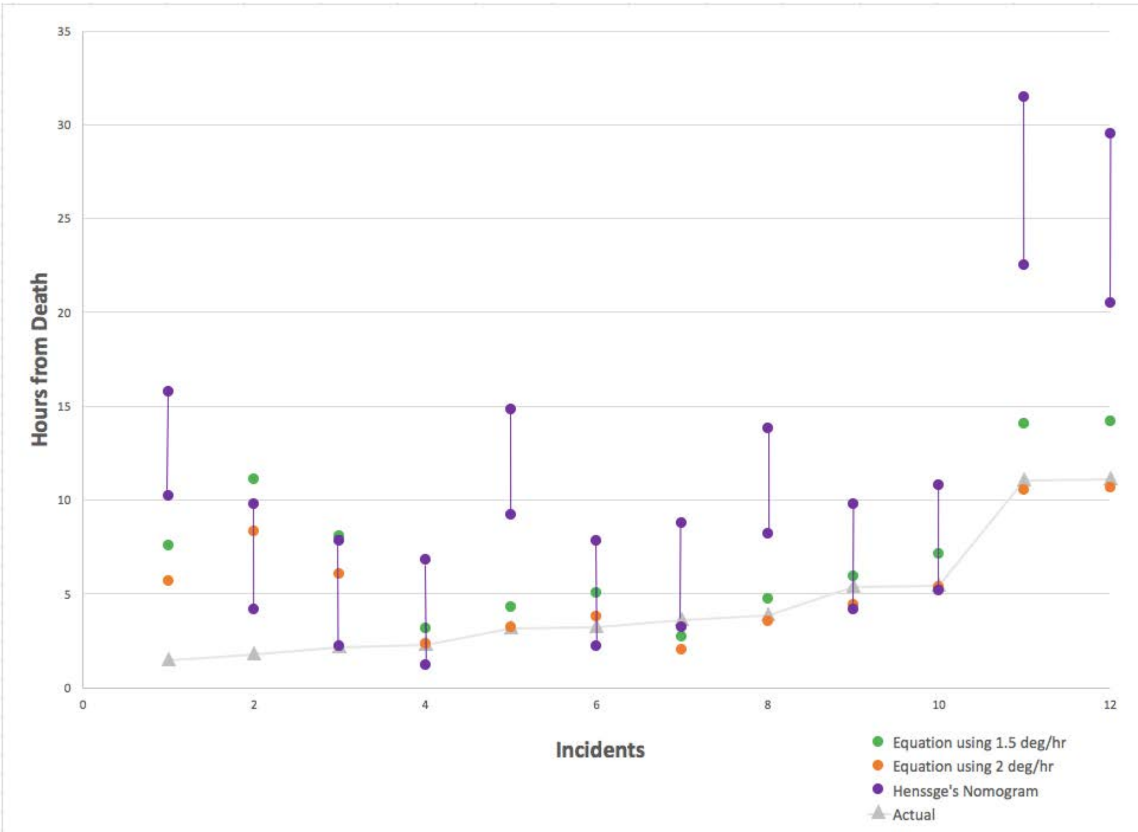

Figure 2.4 Actual time of death was closest to the Glaister Equation with a denominator of 2 deg/hr. Comparing time of death through 3 methods. Henssge's nomogram was added into the comparison of the Glaister Equations with both 1.5 and 2 degrees per hour. The nomogram does not produce a whole number like the equation, it gives a range.

The Glaister Equation with a denominator of 2 deg/hr was found to be the method that had the best results.

Although the Glaister Equation with 2 deg/hr as the denominator had the most results match, the other two methods were not far behind. Therefore, to take another step further with these equations and the results given, I decided to look closer at the absolute error of each one (Figure 2.5).

I assessed the distribution of errors for the three different methods (Figure 2.5). The number of times an absolute error occurred under each given number on the x-axis is seen. These results distinguish the equations in a different way from Figure 2.4. Figure 2.4 showed an equation accuracy evaluation whereas Figure 2.5 shows directly where the error of each method occurs. A better visualization of differences between the methods is seen. The Glaister Equation using 2 deg/hr had a high occurrence of absolute errors under 1. The number of times an error occurred in any other value was very low. The Glaister Equation using 1.5 deg/hr as the denominator had a consistent number of errors, ranging anywhere from 2-4 times, in almost every residual given, which is not ideal. Henssge's nomogram

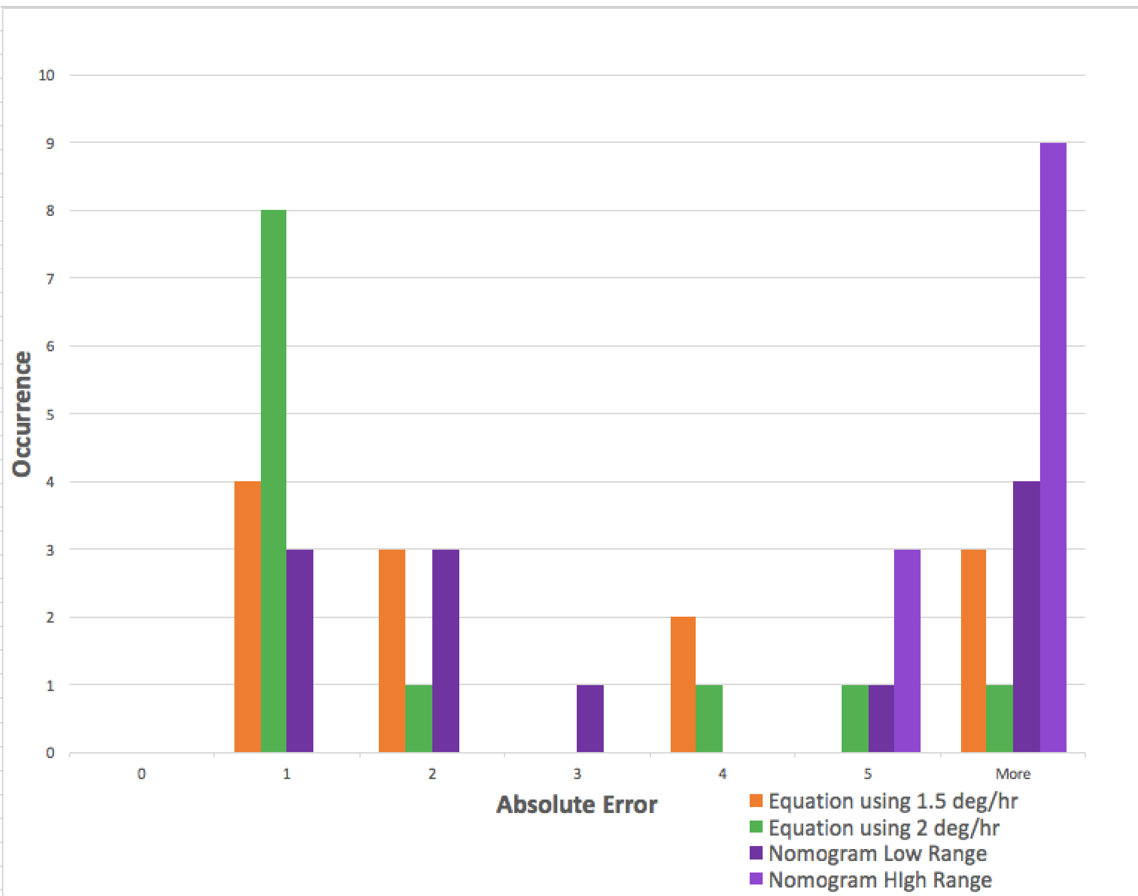

Figure 2.5 Distribution of residuals for rate. When comparing the Glaister Equation with both the 1.5 degrees per hour and 2 degrees per hour, an absolute error was found for each. Most of the residuals were smaller than 1 hour when using the equation with a denominator

of 2 deg/hr. The equation using a denominator of 1.5 deg/hr had almost half of their residuals above 3.

also had a high rate of error in almost every residual given, and even had its most occurrences when the error was higher than 5. If there is going to be a high error rate, it is best to see that when the residual is under 1, showing then that the error is small. Therefore, the Glaister Equation using 2 deg/hr as the denominator is the method that stands out here. Since Figure 2.4 did not show a huge difference between the three different methods, performing a distribution of residuals for these different methods can confirm that the Glaister Equation using 2 deg/hr is the best one out of the three.

2.5 Ambient Temperatures Effect on Error

A noticeable trend was found when looking at each incident on another level. There seemed to be a potential relationship between ambient temperature and the error. When observing each case, I noticed that when the ambient temperature was lower, there almost always was an error in that method's prediction. I wanted to see how true this hypothesis was, and also what the limit of the ambient temperature that began this error could be. Therefore, I plotted the error of each of the three methods against ambient temperature (Figure 2.6). However, since the Glaister Equation using 2 deg/hr as the denominator was found to be the best method previously, I added a connecting line to that one so it could be more easily seen.

Figure 2.6 shows that overall that there are higher data points near the left side of the chart compared to the right side. Not excluding any method and observing, it can be inferred that as the ambient temperature decreases, there is a greater chance of an error occurring. When solely looking at the Glaister Equation using 2 deg/hr as the denominator, it is found that anything above 13 degrees Celsius had an extremely low, and almost little to no error. Anything that was below 13 degrees Celsius appeared to have a larger error. Although there were two points that showed to have a low error, majority of the points below 13 degrees Celsius did have a higher error.

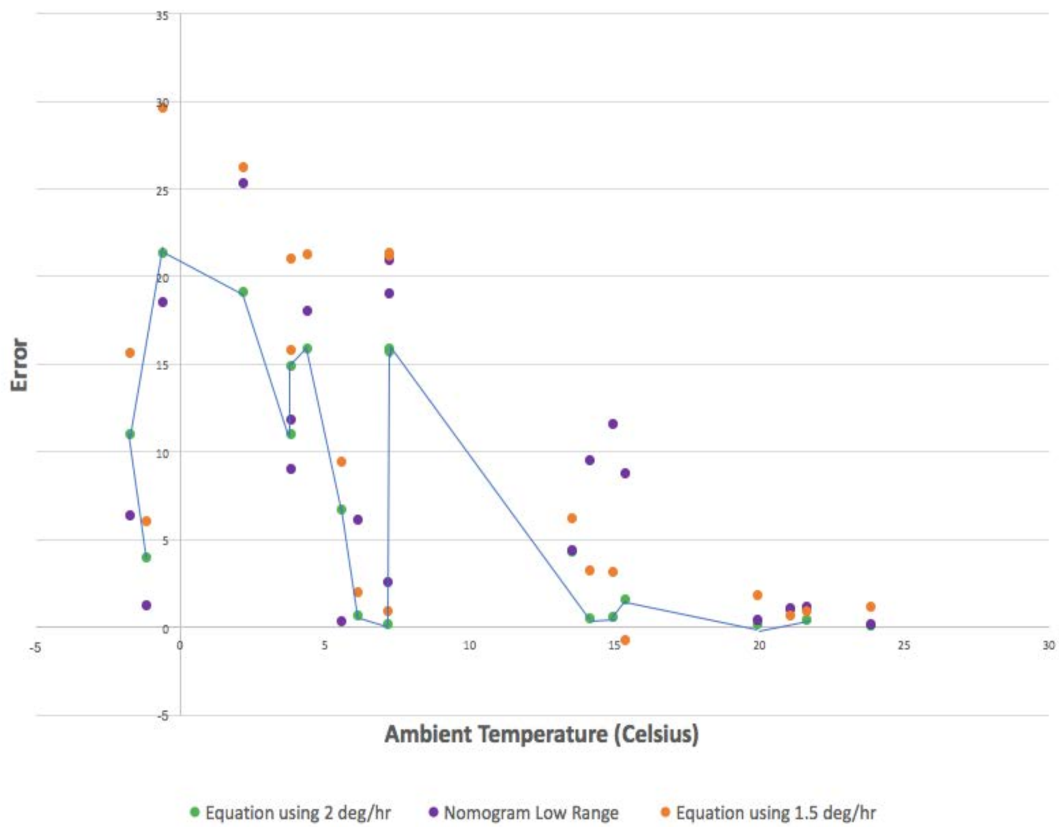

Figure 2.6 Ambient temperatures effect on time of death. As the temperature decreased, the error was found to be greater. Overall, data above 13 degrees Celsius gives a very low error, while data below 13 degrees Celsius gives a very high error.

These results led me to form ideas about other factors that should be added into a new equation. Ultimately, collecting and analyzing the ambient temperature data was going to help in discovering a new time of death equation that is consistently more accurate.

CHAPTER 3

IMPROVING THE EQUATION

3.1 A New Equation

Although the Glaister Equation with 2 deg/hr as the denominator was the closest method, it was obvious that it was missing a very important detail, the ambient temperature. Ambient temperature plays a huge role when it comes to time of death. A body in a temperate room will lose heat much slower than one in any icy, flowing stream. While a body in a hot environment, such as in Phoenix, Arizona, in August will gain heat (Lyle, 2008). Therefore, coming up with a new equation that interpreted ambient temperature within, would be key.

Because the Glaister Equation was not completely wrong or inaccurate 100% of the time, tweaking that equation was a starting point. The first equation that I came up with has three steps. The first step is to do 98.7 degrees Fahrenheit minus the ambient temperature, which will give you “x”. Second, I wanted to make a multiplier that basically stood for the ambient temperature. The ambient temperature causes a change in the rate at which the body cools. The colder the ambient temperature, the higher the body temperature rate would be. Therefore, I turned ambient temperature into a ratio to represent that if the ambient temperature was super cold, the body would cool at a faster rate, and if the ambient temperature was really hot, it would cool at a slower rate or maybe even rise. So, the second step is (98.7 degrees Fahrenheit + "x") / (98.7 degrees Fahrenheit), which equals "y". Then finally the last step is (98.7 degrees Fahrenheit – the body temperature) / (1.5 * "y") ^2.5. The numerator of the equation is identical to the Glaister Equation with having 98.7 degrees Fahrenheit minus the body temperature of the decedent. The denominator has 1.5 which stands for the rate of deg/hr, just like in the original Glaister Equation, but then is multiplied by "y" which is a calculation of ambient temperature, and all raised to an exponent of 2.5. 2.5 is an exponent that magnifies the changes of the rate from ambient temperature. Therefore, I named this equation "Adjusted Glaister Equation".

3.2 Finding More Equations

Ten of the fifteen points gave a time of death result that was closer to the Adjusted Glaister equation than to the Glaister Equation using 2 deg/hr as the denominator. In those 10 points, the result that the Adjusted Glaister equation computed, in comparison to the Glaister Equation's results, not only gave a more accurate time, but they were more accurate by far.

I wanted to see why those 5 other data points gave a time of death result that was closer to the Glaister Equation using 2 deg/hr. By looking deeper at every factor in those sets, they all had something in common. Those 5 data points had body temperatures of the following: 92.3, 94, 91.6, 94.6, and 91.1 degrees Fahrenheit. The body temperatures that gave results that matched closer to the new equation ranged anywhere from 87.3 – negative 9 degrees Fahrenheit. The conclusion then came about that if a body temperature is under 87.3 degrees Fahrenheit the Adjusted Glaister equation should be used, and if the body temperature is above 91.1 degrees Fahrenheit then the Glaister Equation with 2 deg/hr should be used. Following these protocols led to highly accurate time of death results, however I wanted to continue searching and find something even more accurate.

I began with Newton's law of cooling, in which the rate of change of the temperature of an object is proportional to the difference between its initial temperature T_0 and the ambient temperature T_a. At time t, the temperature T_t can be expressed as $T_t = T_a + (T_0 - T_a)e^{-kt}$, where k is the decay constant. I solved for t, given T0 is 37C (98.6F), Ta is ambient and Tt is measured:

$$t = \frac{\ln((Tt - Ta)/(T0 - Ta))}{-k}$$

But k will be dependent on weight. Because size reflects volume (that affects heat capacity) in the third power, and surface area (that affects heat loss) in the second power, I used weight in the power of (2/3).

I used the freely available (for evaluation in academia) software Eureqa (Nutonian, Somerville, MA), a proprietary A.I.-powered modeling engine that automates formulation of empirical equations by assessing errors and comparing estimates to real data. I used the residuals as a direct measure of error, and asked Eureqa to use two variables: $W^{2/3}$ and $\ln(\frac{T_{body} - T_{ambient}}{37 - T_{ambient}})$, where W is weight in kg, T_{body} and $T_{ambient}$ are measured body and ambient temperatures (C) respectively. I chose an equation that gave a relatively low error but was not too complicated:

Eq. 1: $PMI_{est} = 3.421 + 1.233e(-15) * 3.651^{W^{2/3}} - e^{(17.393*\ln(\frac{T_{body}-T_{ambient}}{37-T_{ambient}}))}$

The second argument is multiplied by a very small number and can be dropped without adding much error:

Eq. 1.1: $PMI_{est} = 3.421 - e^{(17.393*\ln(\frac{T_{body}-T_{ambient}}{37-T_{ambient}}))}$

Simplified further to:

Eq. 1.2: $PMI_{est} = 3.421 - (\frac{T_{body}-T_{ambient}}{37-T_{ambient}})^{17.393}$

To use temperature in degree (F), simply replace 37 with 98.6.

3.3 Accuracy of New Equations

The Adjusted Glaister equation did give more accurate results than any previous method, but after running Eureqa, another equation (Eq. 1.2), was found to give even better results (Figure 3.1).

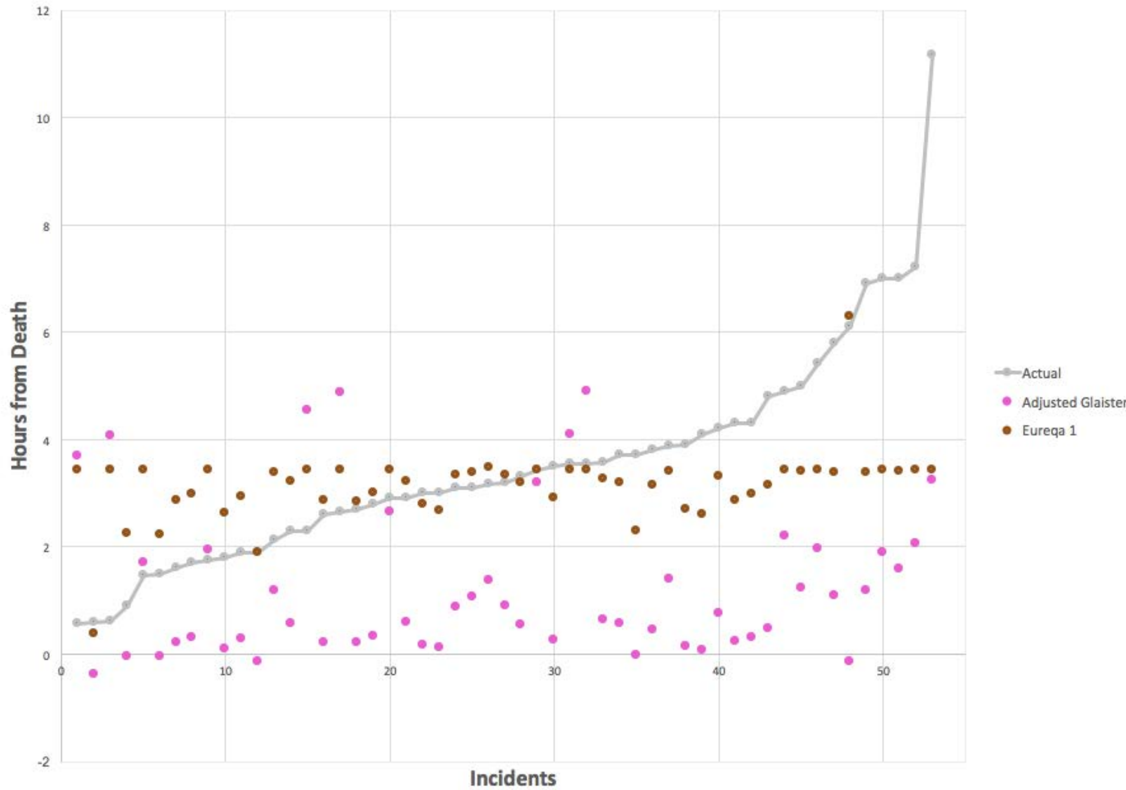

Figure 3.1 Eureqa 1 shows the most accurate PMI. In comparison to the Adjusted Glaister equation, the Eureqa equation shows to be more accurate and closer to the actual time of death.

Since I previously discovered that the Adjusted Glaister equation was only more accurate under certain circumstances (body temperature below 87.3 degrees Fahrenheit), I wanted to see how the body temperature affected all of these different methods as a whole (Figure 3.2). If the Eureqa equation consistently stayed accurate even with the change of body temperature, then it would be confirmed that it is the best method to finding the real time of death of a decedent.

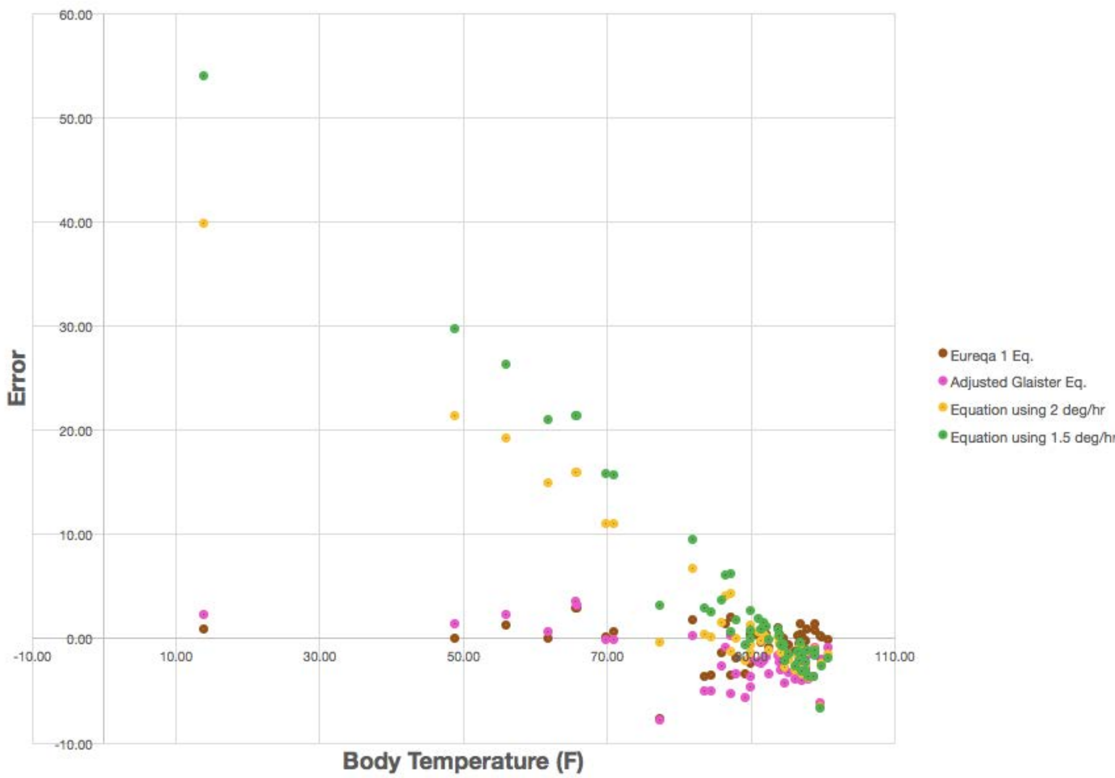

Figure 3.2 The Eureqa equation is the most accurate at any body temperature change. When the body temperature is around 80-100 degrees Fahrenheit, it is seen that any of the methods can be used since they have a low error. However, as the body temperature drops, the error climbs for the Glaister equation using 1.5 deg/hr and 2 deg/hr. The Adjusted Glaister equation does not seem to be as accurate in the high body temperatures but does have a steady low error as the body temperature drops. The Eureqa equation consistently has a low error regardless of the body temperature.

As seen in Figure 3.2, regardless of body temperature ratings, the Eureqa equation proved to be the most accurate. As body temperature dropped, both Glaister equations with either denominator had a very high error. The Eureqa equation was found to be the most constant to produce an error of 0 or extremely close to 0, regardless of any other factor.

However, it is important to note here that the dataset we used (Appendix) for optimization is a relatively low PMI (0-7 hours). The Adjusted Glaister equation, and Eureqa 1 are found to be good at approximating within half of that range (0-3.5 hours).

The half is due to the fact of using absolute error as a measure which gives the same weight to errors regardless of the range of answers. The larger the PMI is, the larger the error is from those 2 new equations.

CHAPTER 4

COMPARISONS OF THERMOMETERS

4.1 Old vs New

As mentioned earlier, two different thermometers were consistently used in my study whenever I went to the field to measure a temperature. The first thermometer, which is used currently by the Northern Regional Medical Examiner's Office, is a Grainger General Digital Plastic Pocket Thermometer (Figure 1A). The second thermometer is a Cole-Parmer Digi-Sense Traceable High-Accuracy Fridge/Freezer Thermometer with Calibration (Figure 1C). It is important to note that the temperatures taken at every scene were in Fahrenheit. Although it is scientifically known to use Celsius, the Investigators I worked with use Fahrenheit every day. Even though my data was taken in Fahrenheit, a simple equation converter can be used to convert the data to Celsius if need be. The point of using two different thermometers was to test the accuracy and see if there was a significant difference between the two, and then determine how that difference ultimately effected time of death in cases.

At every scene I was able to attend, both thermometers were used in order to take the ambient temperature as well as the body temperature of the decedent. Whether the case was a witnessed death or not, the temperature readings were still taken and written down. Knowing the time of death was not as important here since the first focus was on the difference of the thermometers.

The temperature was taken the same exact way for both thermometers. The ambient temperature was taken by having the thermometer in the air near the body until a still value appeared. The body temperature was taken by inserting the thermometer tightly into the axilla of the decedent and waiting until a still number appeared. A comparison of the two different thermometers was made (Figure 4.1).

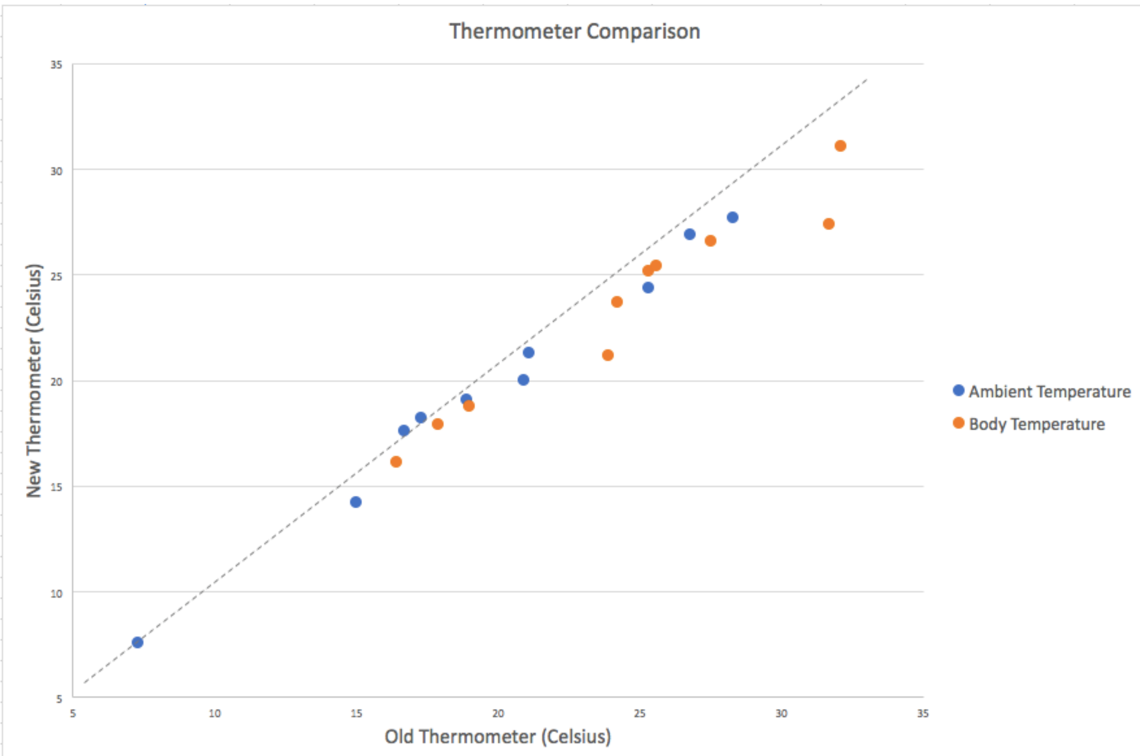

Figure 4.1 The new thermometer almost always measures lower temperatures. Both ambient and body temperature were taken with both thermometers at scenes. Although majority of them were close, the two thermometers give off different readings. The body temperature was found to generally be hotter with the old thermometer.

The x-axis represented the old thermometer while the y-axis represented the new thermometer. The blue dots symbolized the ambient temperature and the orange dots symbolized the body temperature. A dashed line with a slope of 1 was inserted, to show if the two thermometers gave the same reading, where they should have matched then. Through this observation, it can be inferred that the new thermometer almost always gave a lower reading. The big question comes into play, does this effect time of death in cases? If it does, how does it effect it? Would a specific thermometer really be the determining factor when trying to determine time of death?

4.2 Effect of Precision on PMI Estimation

Since the Glaister Equation using 2 deg/hr as the denominator was the most accurate at first, I decided to use it to examine how inaccuracies in temperature measurements will affect PMI estimation. When using that equation, I found out that one degree difference would give a 30 minute difference. When speaking to New Jersey State Medical Examiner Dr. Andrew Falzon, he confirmed that any output of the equation under an hour of the actual time of death was considered good. Any output of the equation that was under a half hour of the actual time of death was considered great, and any output of the equation that was more than hour, was considered not reliable. Therefore, when looking at these two different thermometers, if the difference between the two readings was 2 degrees or less it was still satisfying in regard to the equation, but if the difference was anything above 2 degrees, that was unacceptable.

As for the new equation that was brought up in Chapter 3, a different range was found. A one degree difference only gave a 6minute difference in regard to time of death, and a 2-degree difference gave a 15minute difference. The range for the new equation allowed a larger range for error in the thermometer reading due to the calculation being more complex in comparison to the Glaister Equation using 2 deg/hr.

Out of 20 sets of different temperature readings, 12 of those readings had a difference of less than 1 degree, which would give a very accurate time of death. 5 out of 20 of those readings had a difference that was between 1 and 2 degrees, which was still considered good and would give under an hour difference in the equation. 3 out of the 20 readings produced an error larger than 2 degrees which would have generated a PMI difference of over an hour. If using these 20 sets of readings into the range with the new equation, 19 out of 20 of the readings would have given a very accurate time of death, and one data point would have generated a PMI difference of over an hour.

4.3 Conclusion

The three current methods to determine time of death used in Forensics today were evaluated. The Glaister Equation using both 1.5 deg/hr and 2 deg/hr as the denominators, as well as Henssge's nomogram. Each of these methods were found to be flawed and did not consistently give accurate results. Along with my study, other studies in the past have found similar results of these methods not being precise. Hubig *et al* advised that in a critical evaluation of the Henssge nomogram method using 84 human cases, PMI in 57.1% of cases did not fall within 95% confidence interval and that the method overestimated PMI for bodies with high mass or large surface area (Brooks, 2016). I found that out of the three methods, the Glaister Equation using 2 deg/hr as the denominator gave the best results but still was not the greatest.

Taking a look at other factors, it was noticeable that the ambient temperature played a significant role in body temperature dropping after death. By tweaking the Glaister Equation and adding in some detail, a new calculation was formulated. If the body temperature is above 91.1 degrees Fahrenheit, then it is best to use the Glaister Equation using 2 deg/hr as the denominator. However, if the body temperature is found to be under 87.3 degrees Fahrenheit, then the Adjusted Glaister equation should be utilized. Taking a step further and using the A.I. Eureqa, another equation was discovered. The accuracy of real time of death compared to any of the other methods was found to be closest to the Eureqa equation. When looking at body temperatures effect, the Eureqa equation still showed to consistently give the best results when the PMI is below 7 hours, compared to any other method.

4.4 Discussion

Due to the complexity of discovering time of death, it has been studied for hundreds of years. There is no single factor that will accurately indicate the time of physiological death. It is always a rough estimate. But when the principles are properly applied, the Medical Examiner can often estimate the physiologic time of death with some degree of accuracy (Lyle, 2008). Many factors end up playing a role in time of death, which makes it almost impossible for there to be one specific answer that could work for every decedent's body no matter what influencing outside factors there are. However, equations can try to be calculated in order to get as close as possible to the real time of death.

I found by adding in ambient temperature, the Adjusted Glaister equation gives extremely accurate results when the body temperature is under 87.3 degrees Fahrenheit.

If the body temperature is above 91.1 degrees Fahrenheit, then the Glaister Equation using 2 deg/hr as the denominator should be used. However, after running Eureqa and trying to just find one equation that would fit best, an equation was produced that gave the most accurate results. In my study, it was found that the Eureqa equation does give the best results with a low PMI, compared to any of the previous methods currently used. As of now, I believe this is the best way to determine time of death and get the most accurate results. More data that has a wider range will only continue to improve equations.

Scientists are coming up with different equations and methods to find time of death, but unfortunately, they hardly ever make it to the field. Scientists and investigators should be constantly experimenting with different equations and methods in order to find a concrete answer for determining the time of death. If equations are discovered but never practiced, the research done is never going to lead to better practice.

APPENDIX

Case	PMI (hr)	T body (F)	T ambient (F)	Mass (lb)	Ln(T-T/T-T)	T body (C)	T ambient (C)	Mass (kg)	Ln(T-T/T-T)
A	0.57	66.00	40.00	192.00	-0.81	18.89	4.44	87.09	-0.81
1	0.60	100.80	65.30	198.40	0.06	38.22	18.50	89.99	0.06
31	0.90	99.10	47.30	106.00	0.01	37.28	8.50	48.08	0.01
B	1.47	87.30	56.50	231.00	-0.31	30.72	13.61	104.78	-0.31
2	1.50	99.00	59.20	182.10	0.01	37.22	15.11	82.60	0.01
12	1.60	97.00	48.40	173.70	-0.03	36.11	9.11	78.79	-0.03
20	1.70	96.10	44.20	80.50	-0.05	35.61	6.78	36.51	-0.05
C	1.75	82.00	42.00	113.00	-0.35	27.78	5.56	51.26	-0.35
17	1.80	97.90	46.20	228.20	-0.01	36.61	7.89	103.51	-0.01
9	1.90	96.60	48.90	163.80	-0.04	35.89	9.39	74.30	-0.04
13	1.90	99.90	46.20	163.40	0.02	37.72	7.89	74.12	0.02
D	2.12	86.60	30.00	134.00	-0.19	30.33	-1.11	60.78	-0.19
E	2.28	94.00	45.00	138.00	-0.09	34.44	7.22	62.60	-0.09
F	2.28	56.00	36.00	212.00	-1.14	13.33	2.22	96.16	-1.14
25	2.60	97.00	48.60	131.00	-0.03	36.11	9.22	59.42	-0.03
G	2.65	14.00	-9.00	112.00	-1.54	-10.0	-22.78	50.80	-1.54
18	2.70	97.30	55.00	213.00	-0.03	36.28	12.78	96.62	-0.03
10	2.80	96.60	58.50	145.50	-0.05	35.89	14.72	66.00	-0.05
H	2.90	71.00	29.00	154.00	-0.51	21.67	-1.67	69.85	-0.51
35	2.90	94.10	47.30	144.40	-0.09	34.50	8.50	65.50	-0.09
22	3.00	97.50	54.90	234.60	-0.03	36.39	12.72	106.41	-0.03
24	3.00	97.80	47.30	141.50	-0.02	36.56	8.50	64.18	-0.02
5	3.10	91.90	48.20	147.90	-0.14	33.28	9.00	67.09	-0.14
19	3.10	90.10	46.20	173.10	-0.18	32.28	7.89	78.52	-0.18
I	3.17	92.30	75.10	265.00	-0.31	33.50	23.94	120.20	-0.31
J	3.20	91.10	43.10	144.00	-0.15	32.83	6.17	65.32	-0.15
30	3.30	94.60	49.80	101.00	-0.09	34.78	9.89	45.81	-0.09
K	3.42	70.00	39.00	196.00	-0.65	21.11	3.89	88.90	-0.65
8	3.50	96.80	49.80	149.70	-0.04	36.00	9.89	67.90	-0.04
L	3.55	62.00	39.00	137.00	-0.95	16.67	3.89	62.14	-0.95
M	3.55	49.00	31.00	166.00	-1.32	9.44	-0.56	75.30	-1.32
N	3.57	94.60	59.70	178.00	-0.11	34.78	15.39	80.74	-0.11

11	3.70	94.30	47.30	136.90	-0.09	34.61	8.50	62.10	-0.09
27	3.70	98.80	72.00	209.40	0.01	37.11	22.22	94.98	0.01
29	3.80	95.40	52.50	154.30	-0.07	35.22	11.39	69.99	-0.07
O	3.88	91.60	71.10	200.00	-0.29	33.11	21.72	90.72	-0.29
28	3.90	97.70	49.30	166.40	-0.02	36.50	9.61	75.48	-0.02
4	4.10	98.20	60.60	188.30	-0.01	36.78	15.89	85.41	-0.01
33	4.20	92.70	46.60	165.10	-0.12	33.72	8.11	74.89	-0.12
21	4.30	97.20	56.50	218.90	-0.03	36.22	13.61	99.29	-0.03
32	4.30	96.30	47.50	180.30	-0.05	35.72	8.61	81.78	-0.05
14	4.80	94.80	43.90	138.00	-0.07	34.89	6.61	62.60	-0.07
6	4.90	86.00	64.90	123.90	-0.47	30.00	18.28	56.20	-0.47
3	5.00	90.14	54.10	150.40	-0.21	32.30	12.28	68.22	-0.21
34	5.80	90.10	46.60	200.80	-0.18	32.28	8.11	91.08	-0.18
26	6.10	99.70	50.50	319.70	0.02	37.61	10.28	145.01	0.02
7	6.90	89.40	46.80	129.00	-0.20	31.89	8.22	58.51	-0.20
15	7.00	84.60	50.40	115.30	-0.34	29.22	10.22	52.30	-0.34
16	7.00	87.30	52.30	129.60	-0.28	30.72	11.28	58.79	-0.28
23	7.20	83.70	51.40	141.80	-0.38	28.72	10.78	64.32	-0.38
CB1	11.2	77.4	57.6	234.0	-0.73	25.22	14.22	106.14	-0.73
CB2	5.4	88.0	68.0	121.0	-0.43	31.11	20.00	54.88	-0.43
CB3	0.6	65.8	45.7	192.0	-0.97	18.78	7.61	87.09	-0.97

This data is formatted by three different variables in the "case" column. The cases that are categorized by letters (A, B, C…), are cases that were researched by me in the database at the Medical Examiner's Office. The cases that are categorized as (CB1, CB2, CB3), are cases that I went to directly and retrieved information hands-on. The cases that are categorized by number (1, 2, 3…), are cases from a table in a paper by Mall et al.

REFERENCES

Brooks, J.W. (2016). Postmortem Changes in Animal Carcasses and Estimation of the Postmortem Interval. *Sage Journals*, *53*(5), 929-940.

Hayman, J., & Oxenham, M. (2016). *Human Body Decomposition: Chapter 2 – Algor Mortis and Temperature-Based Methods of Estimating the Time Since Death* (13-52).

Henssge, C., & Madea, B. (2004). Estimation of the time since death in the early post-mortem period. *Forensic Science International*, (144), 167–175.

Kelly, G. (2006). Body Temperature Variability (Part 1): A Review of the History of Body Temperature and its Variability Due to Site Selection, Biological Rhythms, Fitness, and Aging. *Body Temperature, 11*(4), 278–293.

Lyle, D.P. (2008). Time of Death: A Critical Part of the Timeline. *Howdunit Forensics.* F+W Media Inc.

Mackowiak, P.A., Wasserman, S.S., & Levine, M.M. (1992). A critical appraisal of 98.6 degrees F, the upper limit of the normal body temperature, and other legacies of Carl Reinhold August Wunderlich. *JAMA*, *268*(12), 1578-80.

Madea, B. (2015). *Estimation of the Time Since Death (*Third Edition). CRC Press.

Mall G, Eckl M, Sinicina I, Peschel O, Hubig M (2005) Temperature-based death time estimation with only partially known environmental conditions. International Journal of Legal Medicine 119:185–194.

Muggenthaler, H., Sinicina, I., Hubig, M., & Mall, G. (2012). Database of post-mortem rectal cooling cases under strictly controlled conditions: a useful tool in death time estimation. Int J Legal Med. 126(1):79-87

Simpson, K., & Knight, B. (1988). *Forensic Medicine* (9th Edition). London: Bulter and Tanner Ltd. 6.

Smart, J.L., & Kaliszan, M. (2011). The post mortem temperature plateau and its role in the estimation of time of death. A review. Legal Medicine 14(2), 55-62.

Spitz, W. U., Spitz, D. J., & Fisher, R. S. (1993). *Spitz and Fisher's Medicolegal Investigation of Death: Guidelines for the Application of Pathology to Crime Investigation* (Third Edi). Charles C Thomas Publisher.

Spitz, W. U., Spitz, D. J., & Fisher, R. S. (2006). *Spitz and Fisher's Medicolegal Investigation of Death: Guidelines for the Application of Pathology to Crime Investigation* (Fourth Edi). Charles C Thomas Publisher.

Wardak, K., & Cina, S.J. (2011). Algor Mortis: An Erroneous Measurement Following Postmortem Refrigeration. *Journal of Forensic Sciences,56*(5), 1219-21.