The Application of Neural Networks to Inferring Time Since Death In Deer

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Immediately after death many physical changes occur. The body temperature of a carcass begins to decrease and is followed by rigor mortis. Eventually the different stages of decomposition reduce the carcass to its skeleton remains. In wildlife, Time Since Death (TSD) inferences have relied on 1) body temperature [1-5], 2) rigor mortis [2,5], 3) chemical changes in the vitreous fluid [6-8], 4) physical changes in the eye [2,9] , 5) electrical stimulus[10] and 6) the succession of insects after death [11,12].

Wildlife officers commonly use carcass-cooling rates for inferring time since death (TSD). Computer programs have been developed that use the deer carcass thigh temperature to estimate the time of death by applying quadratic equations [4] and regression analysis [13]. Recent investigations have shown that CompuTOD's [13] (a program written by some of these authors) underlying assumptions were erroneous.

This manuscript address 1) the development of a computer program, called NeuralTOD, that uses Neural Networks for estimating TSD and 2) the problems associated with TSD inferences using CompuTOD or other statistical based computer programs.

Materials and Methods

Statistical Analysis was done using Statgraphics Plus (v7.0) from Manugistics, Inc.
Neural Network analysis was done using Aim (v2.0) from AbTech Corporation.

Deer Carcass Temperatures
Deer thigh and/or nasal temperatures from deer carcasses were collected from 4 different studies. These are:

1) *Whole Carcass Study Data*
Thigh and nasal temperature of 33 deer carcasses (n=261 measurements) were collected hourly for 8 hours by field officers of the Tennessee Wildlife Resource Agency and Arkansas Game and Fish Commission. The thigh temperatures were measured by inserting a thermometer into the center of the thigh muscle mass from the inner side. The nasal temperatures were obtained by

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inserting the thermometer into the naso-pharyngeal cavity. Rigor mortis were also evaluated every hour at the jaw, neck, wrist, ankle, elbow and knee and recorded as none, partial or full. Ambient temperature and deer weights were recorded.

2) *Field Dressed Study Data*
Thigh and nasal temperature of 32 deer carcasses (n=359 measurements) were collected hourly for 12 hours by field officers of the Tennessee Wildlife Resource Agency. The temperatures were measured as previously described. Rigor mortis were also evaluated as described. Ambient temperature and deer weight (field dressed) were recorded.

3) *Tennessee Checkpoint Data*
Field officers of the Tennessee Wildlife Resource Agency collected the thigh temperature of 1096 deer at hunter's checkpoints. The thigh temperature was measured as previously described. Ambient temperature and deer weight (field dressed) were recorded. The hunter provided an estimate of the time of kill.

4) *Nebraska Checkpoint Data*
Field officers of the Nebraska Game and Parks Commission collected the thigh and nasal temperature of 225 deer at hunter's checkpoints. The thigh and nasal temperatures were measured as previously described. Officers collected ambient temperature and provided an estimate of the carcass weight (field dressed). The hunter provided an estimate of the time of kill.

Table 1 compares the range of weight, ambient temperature, nostril and thigh temperature, and the post-mortem interval (PMI) of the deer carcass data.

RESULTS

The effect of ambient temperature and carcass weight when estimating TSD.

It is a logical to presume that the rate a carcass cools is influenced by ambient temperature and body weight. Heat is transferred by three general mechanisms including conduction, convection and radiation. Conductive heat transfer is created when two adjacent objects have different temperatures. This occurs when a carcass is laying on the ground. Heat will transfer from the warm carcass to the cooler ground. Convective heat transfer occurs when a fluid separates two objects. In this case, the fluid is considered to be the air and the convection currents are controlled by the surrounding environment. All objects radiate electromagnetic energy. Cooler objects emit less energy than a warm object so that the net effect on a cooler object will be heat gain. In this case, the carcass may gain heat from exposure to the sun. Two theoretical models that describe heat transfer are the Heat Conduction Equation and Newton's Law of Cooling.

Table 1. Comparison of the weight, ambient temperature, nostril temperature, thigh temperature and the post-mortem interval of all data

Data		***Weight***	***Ambient T***	***Nostril T***	***Thigh T***	***PMI (hrs)***
Field Dressed Study Data (32 deer, n=359)	Range	43- 106	18-65	32-103	48-106	0.1-12
Whole Carcass Study Data (33 deer, n=261)	Range	50 - 148	2 - 68	31 - 102	43 -104	0.1 - 24
Tennessee Checkpoint Data (n=1096)	Range	30- 172	20 - 68	N/A	66 - 104	1 - 11
Nebraska Checkpoint Data (n=225)	Range	26-220	22-75	36-99	59-108	0.5 -11

Heat Conduction Equation

Conductive heat transfer is caused by a temperature difference in two adjacent bodies. If the carcass is on the ground and the ground is cooler than the carcass, heat will transfer from the carcass to the ground. The heat conduction formula is given as:

$$q_x = -kA \frac{dT}{dx} \qquad \textit{(equation 1)}$$

where q_x is the rate of heat flow, k is the thermal conductivity, A is the area through which q_x flows, dT/dx is the temperature gradient. The temperature gradient is the change in temperature over a specific length. Therefore the thermal conductivity, boundary area and the temperature gradient all contribute to the heat transfer rate. This suggests that a carcass with minimal contact with the ground may cool slower than if the carcass were in contact with the ground. It also suggests that the material between the ground and the carcass (e.g. fir, weeds, tarp) will affect the cooling rate because different materials have different thermal conductivity.

Newton's Law of Cooling

Newton's law of cooling states that the rate of a cooling body is proportional, under given conditions, to the temperature difference between the body and its surrounding [14]. The formula is given as:

$$\frac{d\Theta}{dt} = -K\,(\Theta - T) \qquad \textit{(equation 2)}$$

where Θ is the temperature of the body, K is a constant of proportionality, T is ambient temperature and t is time. The minus sign (-K) appears because □-T decreases with time when a body is cooling. Rearrangement of equation 2 gives:

$$\Theta(t) = T + (\Theta_0 - T) * \ \mathrm{exp}^{-kt} \qquad \textit{(equation 3)}$$

Where Θ(t) is the body temperature as a function of time and Θ_0 is the initial body temperature. From this equation we can illustrate the difference in cooling rate for varying ambient temperatures using an empirical value of 0.17 for k. For example, if we make the initial body temperature 100 degrees and the ambient temperature 30 degrees, then the body would cool to 80 degrees in two hours. Given the same initial conditions with an ambient temperature of 50 degrees, the body would take 3 hours to cool to 80 degrees.

It is clear from this exercise that a change of 20 degrees in ambient temperature has a significant effect on the cooling rate. Theoretically then, a carcass cools faster in cold temperatures (T=30) than in warm ambient temperatures. In other words, if one was to measure the thigh temperature of a carcass and did not account for the ambient temperature there could be an error of 1 hour in estimating TSD. Also note that Newton's Law of Cooling suggests that the final temperature of the carcass will be the ambient temperature. This may or may not be the case because it is known that a decaying carcass may actually generate heat because of the chemical processes that occur during decay [15,16].

Next we investigated the effect of weight and ambient temperature on the cooling rate of a carcass using multiple regression and discriminate analysis.

Multiple Regression Analysis

Multiple Regression Analysis was performed on the Field Dressed Study data. The dependent variable was the postmortem interval (PMI) and the all the other variables (thigh temperature, nasal temperature, carcass weight, and ambient temperature) were considered independent. Table 2 shows the calculated model that fitted the results.

Table 2. The calculated model fitting the Multiple Regression results

Variable	Coefficient	Standard Error	t-value	Significant Level
Constant	1377.64	24.698	55.77	<0.005
Thigh T	-11.5	0.617	-18.62	<0.005
Nasal T	-3.86	0.604	-6.38	<0.005
Carcass Weight	0.96	0.184	5.22	<0.005
Ambient T	2.37	0.297	7.99	<0.005

The resulting regression equation is:
PMI = 1377.64 +(thigh t *-11.5)+(nasal t * -3.86)+(carcass weight *0.96)+(ambient t*2.37).
The low significance level for the constant term (<0.005) and all the variables (thigh temperature, nasal temperature, carcass weight, and ambient temperature) indicate that they provide useful predictive information. Nevertheless, it should be noted that the coefficient of the carcass weight (0.96) and the ambient temperature (2.37) have less predictive influence within the calculated model.

Discriminate Analysis

In order to evaluate the relative percentage contribution of each variable (thigh temperature, ambient temperature and weight) the data was analyzed by discriminate analysis. Discriminate analysis is useful to classify quantitative data into groups that have predictive value.
The result of discriminate analysis for post-mortem intervals is shown in Table 3.

Discriminate analysis classified the data into three (3) components: 1) thigh temperature, 2) ambient temperature and 3) carcass weight. The Field Dressed Study Data (Table 3) indicates that the low relative percentage of the ambient temperature and weight variables and the associated high "significant levels" indicate that they have little predictor usefulness. Analyses of the Tennessee and Nebraska Checkpoint Data (Table 3) indicate that the ambient temperature variable has a low relative percentage contribution (6.50% and 22.86%, respectively) and a low "significant level" demonstrating that it has limited predictor usefulness. On the other hand analysis of the weight variable indicate that the low relative percentage contribution (4.34% and 17.15%, respectively) and the high "significant levels" demonstrated that it also has little predictor usefulness.

The conclusion that can be drawn from discriminate analysis is that, as expected, the temperature of the thigh of a cooling carcass has the greatest statistical effect on the outcome of the post-mortem interval.

Table 3. Discriminate analysis for Post-mortem Interval

	Component	Relative Percentage	Chi-Square Statistic	DF	Significant Level
Field Dressed Study Data (n=359)	Thigh T	99.96	929.02	36	<0.005
	Ambient T	0.04	1.73	22	1
	Weight	0	0.094	10	1
Tennessee Checkpoint Data (n=1096)	Thigh T	89.16	1427.07	258	<0.005
	Ambient T	6.50	240.1	170	<0.005
	Weight	4.34	97.26	84	0.15
Nebraska Checkpoint Data (n=225)	Thigh T	59.99	568.31	369	<0.005
	Ambient T	22.86	289	244	0.025
	Weight	17.15	130.24	121	0.266

It can be concluded from Multiple Regression analysis and Discriminate analysis that: 1) thigh temperature is a significant variable and is the principal predictor when inferring TSD; and 2) the ambient temperature has a limited predictor usefulness when estimating TSD.

Are the Cooling Rates Linear?

A plot of deer thigh temperature versus known time since death is shown on Figure 1. Historically, the rate of heat loss after death has been thought of as linear. Figure 1 demonstrates that the cooling rate can be defined by three stages:

Stage 1: the first stage occurs immediately following death, and may last up to 6 hours. The carcass dissipates heat quickly, demonstrating a rapid temperature decline. For Figure 1, this stage can be described by $y = -0.082x + 102.71$ ($R^2 = 0.987$).

Stage 2: the second stage occurs somewhere between 2 and 8 hours after death and the data indicates that there is a characteristic period when the rate of temperature loss ceases creating a "plateau" region. For Figure 1, this stage can be described by $y = -0.0217x + 84.7$ ($R^2 = 0.965$).

Stage 3: the third stage occurs, sometime after the 6th hour, and is characterized by a noticeable temperature lose. For Figure 1, this stage can be described by $y = -0.0467x + 96.8$ ($R^2 = 0.995$).

The "plateau" phenomena were seen in 28 of 31 carcasses studied in the Field dressed data but

was not observed in the Whole deer data. The plateau phenomenon presents three difficulties:
1) Since the basic tenet of regression analysis is that the data must be linear [17], regression appears to be a poor choice of statistic to predict time since death when thigh and/or nasal temperature is the predictor because the data is not linear.
2) The “plateau’s” occurrence cannot be predicted and may occur anywhere from 2 - 8 hours. Under field conditions it is impossible to predict if a temperature measurement would correspond to Stage 1, Stage 2, or Stage 3.
3) Lastly, it has been common practice to average the cooling rates of many carcasses in order to fortify the regression statistic. Instead of making the data more homogeneous (by decreasing the variance) this practice increases the error of prediction by distributing the plateau region over the entire curve. This may explain why when using parametric based computerized programs the confidence interval for prediction has been so broad.

TABLE 4. Time Frequencies for Full Rigor Mortis (n=30)

Hours After Death	Frequency	Percent
≤1	1	3.3
2 - 3 hrs	9	33.3
4 - 5 hrs	13	43.3
6 - 7 hrs	3	10
8 - 9 hrs	2	6.6
≥10 hrs	2	6.6

The Influence of Rigor Mortis on Field Dressed Carcass Cooling Rate

A plot of thigh temperature versus time since death is shown on Figure 1. An examination of the data indicates that there is a period of time when the rate of temperature loss decreases creating a “plateau” region. Rigor mortis data was collected in association with the temperature data every hour for 12 hours at the jaw, neck, wrist, ankle, elbow and knee. Rigor mortis was recorded as “none”, “partial”, or “full”. Examination of the data indicates that “full” rigor mortis correlates closely with the “plateau” region. Correlation of the rigor mortis with the “plateau” region occurred in 28 of 30 carcasses studied. The remaining 2 carcasses did not exhibit the plateau phenomena. Although the rigor mortis designation is subjective, it is interesting to note that it correlates well with the objective temperature measurement. Table 4 shows the frequency when rigor mortis was completed. Twenty-two (22) deer carcasses (76.6%) reached rigor mortis within 2 - 5 hours.

The plateau region was never observed in any of the 32 whole carcasses. This fact invite speculation that the plateau is somewhat associated with the cooling of field dressed carcasses, but future work will have to prove or disprove this hypothesis.

Thigh/Nasal Temperature Ratio Inferences

It is significant to note that the ratio of the thigh temperature / nasal temperature is characteristically between 0.9 and 1.5 in all the data sets studied. In other words the thigh temperature is typically a few degrees higher than the nasal temperature. This ratio is logical since the nasal cavity is strongly influenced by the ambient temperature. For example 93% (n=228) of the Nebraska checkpoint data was within the 0.9 – 1.5 ratio (thigh T/ nasal T). Only 5.7 % (n=14) of the carcasses had an ratio that exceeded 1.5 (i.e. the thigh T greatly exceeded the nasal T) and 1.3% (n=3) had a ratio below 0.9 (i.e. the thigh T was lower than the nasal T). The deviation from the "normal" ratio infers a disequilibrium in the carcass cooling. This fact offers the investigator an inference that may be applied to field use.

1. If the nasal temperature is higher than the thigh (ratio < 0.8) then it may be speculated that the following scenarios may apply:
   1.1. A carcass may have been driven around in a vehicle but the head was covered
   1.2. A carcass has been washed out excessively, or a portion of the carcass, posterior to the head, has been allowed to cool in a creek.
2. If the nasal temperature is much lower than the thigh temperature and the ratio exceeds 1.5 then some phenomena has occurred that has maintained the thigh temperature but decreased the nasal temperature, such as:
   2.1. Driving the carcass in the back of a vehicle, while the body was covered but the head was exposed.
   2.2. The head has been exposed to rain or snow.
   2.3. The carcass has been transported on top of a vehicle with the head forward.

Thigh/nasal temperature ratios offer the Officer a way of estimating in the field if a deer carcass has cooled in the expected manner or has the carcass been subjected to some temperature alterations that would invalidate TSD estimates using carcass temperatures.

Neural Networks (NN) Analysis

Since the data indicates that 1) the cooling data is not linear, 2) that the regression analysis is an inadequate statistic for TSD inferences, and 3) the plateau region is a confounding factor that cannot be predicted, we decided to evaluate the use of Neural Networks for TSD inferences. Neural Networks (NN) are numeric modeling tools that automatically learn numeric knowledge from a database of examples. Given a database of examples, the software synthesizes a mathematical model of the relationship in the data. NN's do not require that the training database be linear or parametric, only that a relationship exists in the variables. Most neural networks have some sort of "training" rule whereby the weights of connections are adjusted on the basis of presented patterns. In other words, neural networks "learn" from examples, (just like children learn to recognize dogs, from examples of dogs), and exhibit some structural capability for generalization.

For this analysis the data used for training the NN relationship was based on the combined *Whole Carcass* and *Field Dressed* Study data and called Carcass Study Data in Table 5. The training data consisted of the nasal and thigh temperature, deer weight (whole, not field dressed), and ambient temperature. The output or “learned” product was the post-mortem interval. Once the relationship was developed, the algorithm was incorporated into a program written in Visual Basic and named NeuralTOD.

The relationship of a field dressed carcass to whole carcass is described by $y=0.7724x – 1.7465$, ($R^2 =0.9704$) where y is the field dressed weight (lbs.) and x is the whole carcass weight (lbs.). The weights of the field dressed carcass were converted to whole carcass weight using the regression relationship described above.

In order to determine the accuracy of NeuralTOD, the program was tested using the Carcass Study data, Tennessee Checkpoint data, and Nebraska Checkpoint data. Since the accuracy of NeuralTOD would be measured against parametric programs (i.e. CompuTOD [13]) the following error criteria were used:
1) Calculated data was determined to be accurate if the value was within ±60 minutes of the actual value.
2) Calculated data was determined to be in error if the calculated value exceeded 60 minutes of the actual value. Confidence levels for predications could not be used because neural network analysis is not based on parametric statistics. Table 5 compares the calculated data of the respective programs.

The Carcass Study data was used to create the NN model and to develop the NN algorithm. Since 94% of the Tennessee checkpoint data and 70% of the Nebraska checkpoint data was collected within the first 5 hours after death, two algorithms were developed using NN in order to evaluate the best algorithm. One algorithm was developed using the complete training database (12 hours), and a second algorithm was developed using the first 5 hours after death. The total error rate decreased significantly for the algorithm developed for the 5-hour data.

The use of the Carcass Study data to evaluate the neural network algorithm simply reflects how well the model learned the pattern. Table 5 shows that the Carcass Study data has the lowest total error, demonstrating that the algorithm learned successfully to recognize the relationship between thigh T, nasal T, ambient T and weight and its effect on the PMI.

The analysis of the NeuralTOD against new data is a better way to evaluate the accuracy of the program. This was done using the NN algorithm and evaluating it against the Tennessee and Nebraska Checkpoint data. Table 5 shows that in both data sets the algorithm correctly calculated the PMI within ± 60 minutes. If the estimate of TSD exceeded ± 60 minutes, then errors were encountered.

Table 5. Comparison of Error from TSD Calculations

Program	*Database*	*Notes*	*Percent Error ≤60 Minutes*	*Percent Error >60 Minutes*	*Percent Total Error*
CompuTOD	**Carcass Study Data**	**Thigh and Nasal**	**22.5**	**6.4**	**28.9**
12 hour	**database**				
NeuralTOD	**Carcass Study Data**	**Thigh and Nasal**	**0**	**12.6**	**12.6**
NeuralTOD	**Tennessee Checkpoint Data**	**Thigh**	**0**	**22.4**	**22.4**
NeuralTOD	**Nebraska Checkpoint Data**	**Thigh and Nasal**	**0**	**44.3**	**44.3**
5 hour	**database**				
NeuralTOD	**Carcass Study Data**	**Thigh and Nasal**	**0**	**4.9**	**4.9**
NeuralTOD	**Tennessee Checkpoint Data**	**Thigh**	**0**	**6.1**	**6.1**
NeuralTOD	**Nebraska Checkpoint Data**	**Thigh and Nasal**	**0**	**24.8**	**24.8**

The total error rate of the program based on parametric statistics is greater than 28% (i.e., CompuTOD, etc.). The total error rate for the NN algorithm was less than that for parametric statistics. The Field dressed data error decreased from 28.9 % to 4.9%. The Nebraska error decreased from 47.3 % for the 12-hour data set to 24.8 % for the 5-hour data set.

DISCUSSION

We have demonstrated that regression analysis for inferring TSD may give erroneous results, probably because the cooling of field dressed deer is not linear. Interestingly, the cooling rate of whole deer is linear. If the regression models were based on field dressed carcasses then the resultant data could be spurious. NN are based on pattern recognition and are not concerned with a) linearity, b) equal distribution of the variance, or c) Gaussian distributions [17]. The data presented appears to provide a valid means for accessing time since death in deer if the parameters of weight (whole carcass), ambient, nasal and thigh temperature are known.

Determining the ratio of thigh/nasal temperatures allows for making inferences regarding what has happened to a carcass after death. If the ratio is outside the expected limits (i.e. less than 0.9 or greater than 1.5) then the TSD estimate will be in error.

The predication capabilities of NN to data sets that were not used in the training demonstrates it's ability to predict accurate results. This is the case with both the Tennessee and Nebraska Checkpoint data. The error rate in predicting TSD of carcasses that arrived at the checkpoint within the first 5 hours after death ranges from 4.9% to 24.8%. Table 5 also demonstrates that the error increases drastically after 5 hours after death (see 12 hour database). This is probably due to the many environmental factors affecting the carcass.

We have developed a computer program named NeuralTOD which estimates TSD based on the algorithm described. The user enters carcass weight, thigh, nasal and ambient temperature and the program returns the calculated PMI and the calculated time of death. The time of death result should be considered as the mean of a range. For example if the calculated time of death is 10:00 the user must consider that the carcass could have been killed between 9:00 – 11:00.

Wildlife Field Officers will determine if NN are a viable solution for inferring TSD using cooling rates. Until then, this exercise is academic and must be used with caution when making inferences regarding the death of a deer.

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Chart 1. Graph of the cooling rate of a deer carcass with its 3 Components Reggresion Curves