J Forensic Sci, May 2005, Vol. 50, No. 3
Paper ID JFS2004017
Available online at: www.astm.org

Mary S. Megyesi,[1] *M.Sc.; Stephen P. Nawrocki,*[2] *Ph.D., D.A.B.F.A.; and Neal H. Haskell,*[3] *Ph.D.*

Using Accumulated Degree-Days to Estimate the Postmortem Interval from Decomposed Human Remains*

ABSTRACT: Forensic anthropologists often rely on the state of decomposition to estimate the postmortem interval (PMI) in a human remains case. The state of decomposition can provide much information about the PMI, especially when decomposition is treated as a semi-continuous variable and used in conjunction with accumulated-degree-days (ADD). This preliminary study demonstrates a supplemental method of determining the PMI based on scoring decomposition using a point-based system and taking into account temperatures in which the remains were exposed. This project was designed to examine the ways that forensic anthropologists could improve their PMI estimates based on decomposition by using a more quantitative approach. A total of 68 human remains cases with a known date of death were scored for decomposition and a regression equation was calculated to predict ADD from decomposition score. ADD accounts for approximately 80% of the variation in decomposition. This study indicates that decomposition is best modeled as dependent on accumulated temperature, not just time.

KEYWORDS: forensic science, forensic anthropology, forensic entomology, decomposition, accumulated degree-days, postmortem interval

Estimating the postmortem interval (PMI) can be vitally important in a decomposed human remains case. A carefully-constructed PMI estimate can reduce the potential pool of decedents that the remains could belong to and thus can contribute to the eventual identification of the individual. In homicide cases, law enforcement personnel can use the PMI to exclude possible assailants and to corroborate witness testimony. Knowing the PMI can also help to establish the range of natural events and environmental forces that were likely to have affected the remains with the passing of the seasons, permitting a more thorough taphonomic analysis.

Forensic anthropologists and pathologists have traditionally relied on gross observations of the decay of soft tissues to estimate the PMI. Decomposition is usually divided into a few (usually four) broad categories that grade from one to the next in a semi-regular fashion (1–4). Anthropologists generally use their knowledge of their particular environmental region to produce a rough estimate of PMI from decomposition (5–8). Specific benchmarks (such as sloughing of the epidermis or the collapse of the bloated abdomen) may help to establish minimum or maximum time estimates, but in general the process is qualitative in nature.

In contrast, other disciplines such as forensic botany, entomology, and biochemistry have developed more quantitative methods to estimate the PMI, with encouraging results (9–14). Given the right circumstances, these quantitative methods can be used to produce PMI estimates that are accurate to within days or even hours. In general, these methods have been applied when the PMI is relatively short, in time frames measured in days or weeks. For the increased PMI's that are typically encountered by forensic anthropologists, measured in months or years, the application of typological, qualitative approaches seems more reasonable. However, could forensic anthropology benefit from applying more quantitative methods to the study of decomposition?

Soft tissue decomposition is a sequential process with numerous small changes occurring throughout. If the broad, qualitative categories of decomposition were redesigned to specifically reflect these smaller sequential changes, the state of decomposition could be described more precisely, as a quasi-continuous or continuous variable. Instead of using a few qualitative categories of decomposition, the use of a greater number of quantified stages with assigned point values to express decomposition would increase the statistical power of hypothesis testing and could provide more information about the relationship between decomposition and the PMI.

A comparison of anthropological approaches to the study of decomposition with the more quantitative sciences (such as entomology) reveals an even more glaring difference. In the 50 years of research on gross decomposition processes, there have been no comprehensive attempts to correlate the overall physical changes that occur with the variable that affects this process the most: temperature. Just as maggot growth and development are correlated with accumulated temperature, so should the soft tissue decomposition that is driven by the activity of bacteria and insects. For years anthropologists have modeled decomposition as dependent on time only; this research suggests that decomposition is more accurately modeled as dependent on accumulated temperature.

A method that can more accurately estimate PMI from decomposing human remains would be extremely useful in cases where insects, plants, or soil samples are not present, not collected, or not collected properly. The present study attempts to inject a more quantitative approach into traditional anthropological thinking by viewing the decomposing body as a stopwatch whose hands are driven by temperature.

[1] Department of Anthropology, Michigan State University, East Lansing, MI.
[2] Associate Professor of Biology and Anthropology, University of Indianapolis, Indianapolis, IN.
[3] Associate Professor of Biology, St. Joseph's College, Rensselaer, IN.
* This work was partly presented as a poster presentation at the 54th annual American Academy of Forensic Sciences meeting, Atlanta, GA, February 2002.
Received 17 Jan 2004; and in revised form 5 June 2004 and 2 Oct. 2004; accepted for publication 9 Jan. 2005; published 6 April 2005.

Materials and Methods

The Study Sample

A total of 68 human remains cases were selected from the case files of the two junior authors (Table 1). All cases were essentially complete with no missing body parts so that decomposition could be scored for the entire body in a standardized fashion. No burned, buried, or submerged remains were used in this study.

Remains found outdoors were the most common in the dataset, accounting for 57 cases. These came from a variety of settings including woods, fields, and ditches. Thirteen cases were found in full sun, 15 in shaded areas, and 29 in areas that received a mix of sun and shade. Remains found indoors were also included in this study. These included three found in houses, three found in apartments, two found in residential trailer homes, one found in a condominium, one found in a cabin at a state park, and one found in an abandoned building, for a total of 11. For some of the indoor cases, the temperatures inside the building were likely to be nearly the same as those recorded outside due to open windows and doors. In others, however, the inside temperatures were probably different from the outdoor temperatures. Indoor cases were analyzed with the entire group and were then examined individually for outlying values.

Forty cases were found clothed normally (with underwear, pants or shorts, shirt, and usually shoes) and 26 were found nude or only wearing one small piece of clothing such as a tee shirt or an undergarment. One indoor case was fully clothed and covered with several blankets and sleeping bags (Case # 73, Table 1). One outdoor case was found in a sleeping bag and wrapped with a plastic tarp and bound with nylon rope (Case # 90, Table 1). While this type of unusual treatment could introduce error into the sample, they represent types of cases found in the practices of forensic investigators nation-wide and therefore serve as realistic tests for any method of PMI estimation. All 68 cases had evidence of insect access, and none had been sufficiently sequestered to deny their access. Later analysis clearly indicated that the covered bodies were not significant outliers in any of the regression plots, justifying their continued inclusion in the dataset as a whole.

The mean age of death for this sample is 32.3 years (s = 15.9 years). The youngest age recorded was 11 and the oldest was 72. Twelve individuals were under the age of 18. Age was not known or recorded in five adult cases. No children younger than 10 years of age were included in the dataset so that differences in decomposition due to body size would be minimized. Ancestry was recorded in 30 cases, most being of European or African descent. There were 39 females and 29 males. All individuals died between 1980 and 2000. All cases except two were positively identified individuals.

Only cases with a known PMI of less than one year were used because soft tissues are rarely present beyond one year postmortem in most temperate climates. Figure 1 shows the distribution of the lengths of the postmortem intervals. The mean was 30.1 days with a range of 2 to 200 days (s = 46.5 days). The majority of cases came from Indiana ($n = 15$) and Illinois ($n = 13$), although 17 other states are represented, producing a geographically diverse dataset that covers most regions of the United States. Nearly three-quarters of the individuals ($n = 52$) died during the warmer months of the year (May through September), with a peak in August ($n = 16$), although all months are represented by at least one death except December, which had none. Further details regarding other characteristics of the study sample can be found in Megyesi (15).

Measuring Decomposition

The state of decomposition at the time of discovery was assessed and scored from photographs of the remains. Photographs were usually taken by police personnel, crime scene technicians, or by the authors. Only cases that had clear pictures of all parts of the body were used. In most cases, there were pictures of the deceased in situ and during autopsy. Autopsy photos were helpful because clothing had been removed, providing a view of tissues and bones that had been obscured in the scene photographs. In some cases, photographs were supplemented with detailed taphonomic data provided in original case notes of one of the authors (SPN). The senior author scored all cases without reference to the known PMI.

Decomposition was scored using a modification of Galloway et al.'s (16) method. These categories were intended to describe the decomposition process as it occurs in southern Arizona and Galloway and colleagues caution that the stages are not necessarily sequential. For the present study, it was necessary to modify their stages into a sequential ranking so that the final decomposition scores reflect the total amount of accumulated decomposition that had taken place. Decomposition is first divided into 4 broad categories: fresh, early decomposition, advanced decomposition, and skeletonization. Stages within each category describe the appearance and general characteristics of the remains. Each stage has an assigned point value starting at "1" (fresh) and increasing one point for each progressive stage. The total number of points received represents the amount of accumulated decomposition that has taken place. Other modifications to Galloway et al.'s method included the removal of adipocere development because this trait seems to occur independently without regard to a specific degree of decomposition (17,18). Mummification does not occur as rapidly in temperate climates and so the stages were altered to reflect the process as it occurs in non-desert regions of the United States. Categories dealing with extreme decomposition (bone surface destruction) and burning were also excluded.

Not all stages of decomposition apply equally to all parts of the body. For instance, limbs do not bloat, nor do they purge decompositional fluid. In order to account for the differential decomposition that occurs in different body segments, the remains were scored independently in three specific areas of the body: (1) the head and neck, including the cervical vertebrae; (2) the trunk, including the thorax, pectoral girdle, abdomen, and pelvis; and (3) the limbs, including the hands and feet. The stages of decomposition were slightly different for each of the three anatomical areas, resulting in three separate scoring strategies. Tables 2, 3, and 4 define the categories and stages of decomposition for each of the anatomical regions along with assigned point values.

The scores of each of the three anatomical regions are combined to produce a total body score (TBS). For example, hypothetical case X is scored as follows: head and neck, stage B4 = 5 points; thorax, abdomen and pelvis, stage B4 = 5 points; limbs, stage B4 = 5 points. The TBS would be $5 + 5 + 5 = 15$. The lowest score a case could receive is 3 (fresh in all regions) and the highest score is 35 (dry bone in all regions).

In a few instances, the decomposition stage varied across one anatomical area (for example, arm and leg decomposition did not match). The point value assigned was the average of the two extremes observed in the area. In a few cases, the decomposition observed did not seem to match the sequence definitions. For instance, in some cases the fingertips, ears, and toes appeared dried out but there was no evidence of skin slippage or discoloration. For these cases, the point value assigned was one that corresponded

TABLE 1—*Case information summary.*

Case #	County, State	Date Died; Found	PMI Days	TBS	ADD	Sex	Age*	OUT/IN/SUN†	Clothing‡	Method of PMI Determination§
4	Owen, IN	9-1-95; 9-13-95	13	22	276.3	F	36	Out/mix	N	Ent
5	Bartholomew, IN	8-15-98; 9-17-98	36	27	763.8	F	25	Out/mix	C	Police
11	Hendricks, IN	7-14-99; 8-30-99	48	29	1108.7	F	39	Out/mix	N	Ent
25	McHenry, IL	6-4-91; 6-8-91	5	12	120.1	M	61	In/apt	N	Ent
27	Jackson, IN	2-24-95; 4-14-95	50	14	406.9	M	20	Out/sun	C	Ent
28	Tippecanoe, IN	6-9-95; 6-20-95	12	15	272.3	M	72	In/Trailer	N	Ent
30	Wayne, IN	7-25-96; 8-25-96	32	28	706.6	F	68	Out/mix	C	Ent
35	Johnson, IN	5-13-97; 11-2-97	170	35	3320.9	F	27	Out/mix	C	Police
36	Fulton, IN	11-11-94; 5-6-95	176	28	723.5	F	37	Out/sun	C	Police
37	Kankakee, IL	7-13-95; 7-15-95	3	15	91.7	F	25	Out/sun	N	Ent
38	Kankakee, IL	4-5-95; 9-22-95	167	32	3318.8	F	13	Out/mix	C	Police
39	Lucas, OH	8-14-95; 9-7-95	25	27	605.7	F	15	Out/mix	C	Ent
40	Monroe, NY	8-8-95; 10-22-95	75	27	1326.7	F	16	Out/shade	N	Police
41	Morgan, IL	6-7-96; 6-13-96	7	13	132.8	M	45	In/apt	N	Ent
42	Pope, IL	8-26-96; 9-1-96	6	15	167.8	M	56	In/cabin	N	Ent
43	Will, IL	9-22-29; 9-29-94	8	11	123.9	M	23	Out/sun	C	Ent
44	Richland, SC	10-27-96; 11-3-96	8	13	142.3	F	37	Out/mix	N	Ent
45	Howard, IN	9-15-95; 11-19-95	66	21	676.2	M	29	Out/shade	C	Ent
47	Rock, WI	9-2-96; 3-20-97	200	26	920.0	F	18	Out/mix	C	Ent
52	Fayette, PA	6-6-95; 6-13-95	8	19	149.4	F	47	Out/shade	C	Ent
53	Missoula, MT	10-17-93; 11-7-93	22	21	91.5	M	. . .	Out/mix	N	Ent
55	Brown, IN	9-27-97; 9-30-97	4	8	64.5	F	18	Out/mix	C	Police
56	Will, IL	7-5-97; 8-10-97	37	24	884.9	F	25	Out/sun	C	Ent
57	Franklin, MO	6-23-96; 8-1-96	40	26	929.1	F	14	Out/mix	C	Police
58	Knox, TN	9-17-90; 9-20-90	4	6	80.2	M	20	Out/mix	C	Police
59	St. Louis, MO	5-4-97; 5-7-97	4	12	69.0	F	58	In/House	N	Ent
60	Andrews, TX	9-10-97; 915-97	6	13	152.6	M	18	Out/sun	C	Ent
61	St. Louis, MO	7-30-97; 8-10-97	12	17	286.4	F	26	In/aband-build	C	Police
62	Escambia, FL	2-27-96; 3-5-96	8	8	91.4	M	37	Out/shade	C	Ent
63	Abbeville, SC	8-25-95; 8-28-95	4	9	94.8	F	35	Out/mix	N	Ent
64	Norfolk, VA	8-17-97; 8-22-97	6	12	148.4	M	32	In/condo	N	Ent
65	Blaine, MT	8-14-98; 8-24-98	11	23	239.8	M	69	Out/sun	N	Ent
66	Bakersfield, CA	9-14-95; 9-18-95	5	14	133.4	F	48	In/apt	C	Ent
67	Marshall, KY	10-21-98; 11-4-98	15	14	215.0	F	41	Out/mix	C	Ent
68	Spokane, WA	5-27-96; 6-14-96	19	18	273.0	F	39	Out/mix	N	Ent
69	Urbana, OH	7-9-97; 9-7-97	61	26	1319.5	F	11	Out/shade	N	Ent
70	Allen, IN	1-3-98; 4-7-98	64	17	360.6	M	42	Out/mix	C	Ent
71	Spokane, WA	5-11-98; 6-9-98	30	25	493.6	F	17	Out/sun	C	Ent
72	Pasco, FL	6-9-99; 6-13-99	5	15	133.1	F	36	Out/sun	C	Ent
73	Shoshone, ID	5-21-99; 7-4-99	45	19	673.0	M	. . .	In/house	C	Police
74	Rock Is., IL	7-3-99; 7-12-99	10	17	220.8	F	34	Out/sun	C	Police
75	Tazewell, IL	8-11-99; 8-17-99	7	13	138.0	F	19	Out/shade	N	Ent
76	Will, IL	5-13-97; 5-26-97	14	12	200.8	F	18	Out/shade	C	Ent
77	Lucas, OH	8-9-99; 1-6-00	149	27	1665.4	F	38	Out/shade	N	Ent
78	Daviess, IN	8-31-00; 9-11-00	12	17	264.1	F	24	Out/mix	N	Ent
79	Columbia, NY	9-16-00; 9-30-00	15	22	213.5	F	43	Out/shade	N	Ent
80	Seminole, FL	9-15-96; 9-17-96	3	11	87.9	M	30	Out/sun	C	Ent
81	Great Bend, KS	6-30-94; 7-3-94	4	13	104.2	M	43	In/Trailer	C	Ent
82	Jefferson, WA	10-3-00; 10-13-00	11	18	120.5	M	48	Out/mix	C	Ent
83	Chattanooga, TN	8-28-00; 9-1-00	5	15	127.6	M	71	In/House	C	Police
84	Marion, IN	2-15-94; 4-5-94	50	18	279.4	F	11	Out/mix	C	Police
85	Portage, OH	8-21-94; 8-25-94	5	10	100.9	F	17	Out/shade	N	Ent
86	JoDaviess, IL	3-28-94; 4-10-94	14	9	62.8	M	38	Out/shade	C	Police
87	Cumberland, PA	8-2-80; 8-6-80	5	17	131.4	F	. . .	Out/shade	C	Police
88	Sterling, IL	8/12/95; 8-13-95	2	13	58.2	M	32	Out/mix	C	Police
89	Morris, NJ	7-28-95; 8-2-95	6	20	173.1	F	34	Out/shade	C	Police
90	Jefferson, IL	7-22-93; 12-5-93	137	27	2370.9	M	. . .	Out/mix	C	Ent
92	Largo, FL	11-1-95; 11-18-95	18	24	325.8	F	40	Out/sun	N	Ent
93	Essex, NJ	10-21-95; 10-25-95	5	3	74.9	F	16	Out/shade	N	Police
94	Dallas, TX	6-3-95; 6-7-95	5	12	104.8	M	22	Out/mix	C	Ent
95	Largo, FL	10-26-94; 10-29-94	4	15	85.4	F	23	Out/mix	N	Ent
96	Franklin, SC	11/27/90; 12-1-90	5	3	55.9	M	24	Out/shade	C	Police
97	LaPorte, IN	4-15-95; 4-16-95	2	3	27.1	M	17	Out/sun	C	Ent
98	Santa Rosa, CA	8-14-97; 8-22-97	9	20	172.5	F	12	Out/mix	N	Ent
99	Boundary, ID	8-3-96; 8-9-96	7	13	118.2	M	15	Out/mix	C	Police
100	Staten IS, NY	4-16-96; 4-19-96	4	6	63.2	M	51	Out/mix	C	Ent
101	NorthPort, FL	3-1-96; 3-7-96	7	14	135.8	M	. . .	Out/mix	N	Ent
102	Hendricks, IN	6-30-00; 7-11-00	12	22	270.6	M	19	Out/mix	C	Ent

* A "—" symbol indicates that age was not available.

† "Out/mix" indicates remains found outdoors exposed to a mixture of sun and shade. "Out/sun" indicates remains found outdoors exposed to mostly sunny conditions. "Out/shade" indicates remains found outdoors exposed to mostly shady conditions. Remains found indoors are indicated as "In/house" or "In/trailer" describing the specific building type. "Apt" stands for "apartment."

‡ "N" indicates remains were found nude. "C" indicates remains were found wearing clothing.

§ "Ent" indicates the PMI was determined by NHH based on insect evidence. "Police" indicates PMI was determined by confessions, suicide notes, or other law enforcement investigative methods.

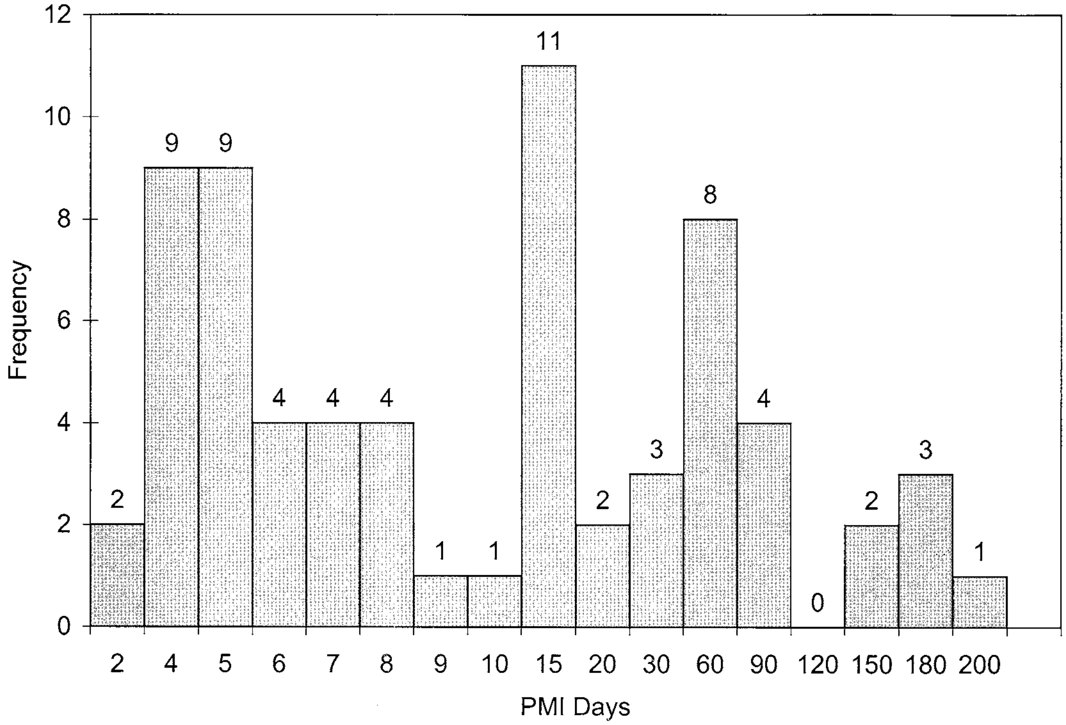

FIG. 1—*Distribution of Cases by Postmortem Interval (n = 68).*

TABLE 2—*Categories and stages of decomposition for the head and neck.*

A. Fresh	
(1pt)	1. Fresh, no discoloration
B. Early decomposition	
(2pts)	1. Pink-white appearance with skin slippage and some hair loss.
(3pts)	2. Gray to green discoloration: some flesh still relatively fresh.
(4pts)	3. Discoloration and/or brownish shades particularly at edges, drying of nose, ears and lips.
(5pts)	4. Purging of decompositional fluids out of eyes, ears, nose, mouth, some bloating of neck and face may be present.
(6pts)	5. Brown to black discoloration of flesh.
C. Advanced decomposition	
(7pts)	1. Caving in of the flesh and tissues of eyes and throat.
(8pts)	2. Moist decomposition with bone exposure less than one half that of the area being scored.
(9pts)	3. Mummification with bone exposure less than one half that of the area being scored.
D. Skeletonization	
(10pts)	1. Bone exposure of more than half of the area being scored with greasy substances and decomposed tissue.
(11pts)	2. Bone exposure of more than half the area being scored with desiccated or mummified tissue.
(12pts)	3. Bones largely dry, but retaining some grease.
(13pts)	4. Dry bone.

TABLE 3—*Categories and stages of decomposition for the trunk.*

A. Fresh	
(1pt)	1. Fresh, no discoloration.
B. Early decomposition	
(2pts)	1. Pink-white appearance with skin slippage and marbling present.
(3pts)	2. Gray to green discoloration: some flesh relatively fresh.
(4pts)	3. Bloating with green discoloration and purging of decompositional fluids.
(5pts)	4. Postbloating following release of the abdominal gases, with discoloration changing from green to black.
C. Advanced decomposition	
(6pts)	1. Decomposition of tissue producing sagging of flesh; caving in of the abdominal cavity.
(7pts)	2. Moist decomposition with bone exposure less than one half that of the area being scored.
(8pts)	3. Mummification with bone exposure of less than one half that of the area being scored.
D. Skeletonization	
(9pts)	1. Bones with decomposed tissue, sometimes with body fluids and grease still present.
(10pts)	2. Bones with desiccated or mummified tissue covering less than one half of the area being scored.
(11pts)	3. Bones largely dry, but retaining some grease.
(12pts)	4. Dry bone.

to the earlier stage of decomposition because the TBS should best reflect how much decomposition had taken place overall. In these instances, if they were scored as B3 = 4 points, it would have indicated that they had already progressed completely through stages A1-B2 when they actually had not. Overall, deviations from the decomposition sequence were rare and the decomposition observed in photographs matched the progression of decomposition outlined in this scoring strategy very well.

Calculating Accumulated Degree Days

Temperature data for the postmortem interval was collected for each case from the nearest National Weather Service Station. All temperature data was in the form of daily averages, calculated as the average of the maximum and minimum air temperatures (dry bulb) for the day. No corrections were performed on any of the temperature data based on distance or any other variable for the calculations of accumulated degree-days for this analysis.

Accumulated degree-days represent heat energy units available to propel a biological process such as bacterial or fly larvae growth. A "base temperature" represents the temperature at which the biological process essentially stops. Forensic entomologists use a base of 10°C or 6°C depending on the temperature at which the fly species ceases to grow and develop (10,12,19,20). Vass et al. (13) state that

TABLE 4—*Categories and stages of decomposition for the limbs.*

A. Fresh	
(1pt)	1. Fresh, no discoloration
B. Early decomposition	
(2pts)	1. Pink-white appearance with skin slippage of hands and/or feet.
(3pts)	2. Gray to green discoloration; marbling; some flesh still relatively fresh.
(4pts)	3. Discoloration and/or brownish shades particularly at edges, drying of fingers, toes, and other projecting extremities.
(5pts)	4. Brown to black discoloration, skin having a leathery appearance.
C. Advanced decomposition	
(6pts)	1. Moist decomposition with bone exposure less than one half that of the area being scored.
(7pts)	2. Mummification with bone exposure of less than one half that of the area being scored.
D. Skeletonization	
(8pts)	1. Bone exposure over one half the area being scored, some decomposed tissue and body fluids remaining.
(9pts)	2. Bones largely dry, but retaining some grease.
(10pts)	3. Dry bone.

because of salt concentrations in the human body, decomposition will occur down to 0°C. Micozzi (4) states that no putrefaction occurs at temperatures less than 4°C. However, neither author backs up these claims with any experimental evidence. Therefore, it is not known at what temperature decomposition processes actually cease.

For the purposes of this study, 0°C is used as the base temperature because freezing temperatures severely inhibit biological processes such as bacterial growth. Accumulated degree-days were calculated for each case by adding together all average daily temperatures above 0°C for all days from death until discovery. Temperatures below 0°C were always recorded as zero rather than as negative values.

Determining the Date of Death

The date of death was recorded for all cases. For 20 cases the date of death was recorded from law enforcement and/or legal records such as a death certificate, suicide note, or confession. For the remaining 48 cases, the date of death was determined from insect evidence by a board-certified forensic entomologist of the American Board of Forensic Entomology (NHH). Entomology is widely regarded as one of the most accurate ways to determine the date of death and it relies on both the pattern and succession of corpse colonization and the life stage of insects collected on, in, and around the body (11,21,22). The entomological assessment of time since death was entirely independent of this study, and in many cases, used slightly different temperature data. The date of death was calculated by NHH for most cases with hourly temperature records (instead of daily averages) from weather stations. Adjustments to weather station temperatures and/or supplemental temperature information was used in some cases to account for specific scene environments where conditions were grossly different from weather station temperatures, such as heated or cooled indoor environments.

The period of time when death likely occurred was determined in all cases, which varied from a few weeks to a few hours. Of the 48 cases where insect evidence alone was used to determine the date the death, only 10 had a range of time longer than 24-h in which death likely occurred. This kind of precision is not uncommon in forensic entomology, especially when the time since death is less than 3 months and temperatures are warm, two conditions that describe the majority of this sample (10,19). For the 38 cases where death likely occurred within a 24-h period or less, we simply used the date in which the majority of these hours occurred. For the 10 cases where entomological evidence determined that death likely occurred during a period longer than 24 h, the average period was only 8.4 days. Therefore, despite the fact that the date of death for the majority of this sample was determined by insect evidence, these dates are independent of decompositional stage and are accurate enough to serve the purposes of this preliminary study.

Statistical Analysis

The theoretical relationship between the variables in this study and TBS represents a quasi-continuous dependent variable and ADD represents a continuous independent variable. Essentially, this study only accounts for accumulated time and temperature to explain the variation in decomposition. Other climatic and contextual factors, such as seasonality, geographic location, sunlight, humidity, rainfall, clothing, peri/postmortem injuries and vertebrate scavengers affect decomposition but frequently cannot be quantified for most forensic cases because it is not possible to determine many of these variables retrospectively at most death scenes (23–26). Our model relies on a retrospective analysis of case photographs and historical temperature data, not controlled field experiments. Thus, while we are not directly controlling for several other factors affecting decomposition, because this is a realistic study sample, these other variables are accounted for indirectly in our error ranges. This is a realistic, preliminary study examining the potential of using ADD and decomposition to estimate the PMI, not a multivariate analysis of everything that could possible affect decomposition. Statistical procedures were conducted using SYSTAT 5.2.1 for the Macintosh and SPSS 10.1.4 for Windows.

Results

Qualitative Observations

The TBS for this dataset ranged from three (fresh) to 35 (dry bone), with a mean of 17.2 ($s = 7.3$, $n = 68$). Not all possible scores are represented in the dataset. For example, cases in the later stages of decomposition with scores from 30 to 35 are not common. See Fig. 2 for the distribution of TBS scores among cases.

A score of 1 point (fresh) for any part of the body was only observed in the five cases whose TBS ranged from three to six. Purging of decompositional fluid from the orifices of the face was only observed in cases with a TBS of 8 to 13 ($n = 19$). Bloating of the abdomen and thorax was observed only in cases with a TBS of 11 to 19 ($n = 34$). The lowest TBS score where post-bloating occurred was 18. All cases with a TBS of 17 and greater had bone exposure of at least one area of the body. The score for the head was always greater than or equal to the score for the thorax or limbs for all cases, which has been observed before (7).

The lowest TBS score in which bone exposure of the head was observed was 14. The lowest TBS in which bone exposure of the thorax and abdomen occurred was 20, and for the limbs it was 21. Many cases had both bone exposure of the head and bloating of the abdomen. All cases with a TBS of 23 and greater had bone exposure of the limbs. Table 5 outlines some characteristics of decomposition and the TBS range in which they were observed in this study. The ADD for all cases ranged from 27.1 to 3320.9, with a mean of 439.01-degree days ($s = 661$, $n = 68$). Figure 3 illustrates the frequency of cases by ADD.

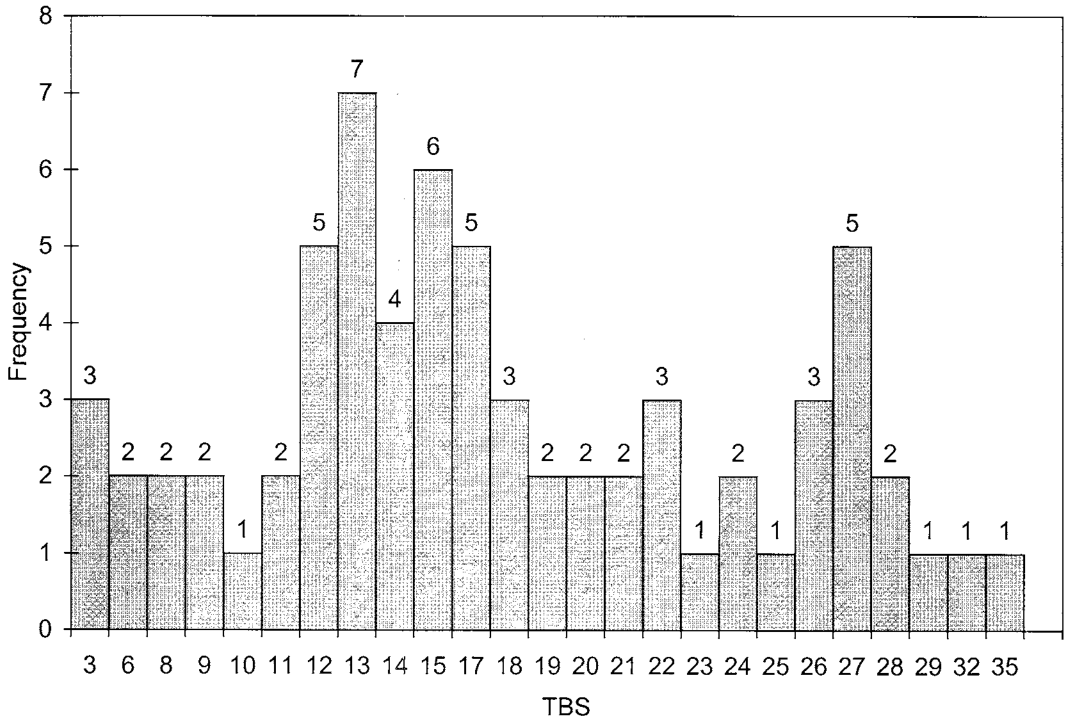

FIG. 2—*Distribution of Cases by Total Body Score (n = 68).*

TABLE 5—*Characteristics of decomposition and corresponding TBS range.*

Decomposition Characteristics:	TBS Range:
Purging from facial orifices	8–13 ($n = 19$)
Bone exposure of head <1/2	14–26 ($n = 34$)
Bloating of abdomen	11–19 ($n = 34$)
Bone exposure of thorax	20–35 ($n = 24$)
Bone exposure of limbs	21–35 ($n = 22$)

Quantitative Analysis

Figures 4 and 5 are plots of TBS vs. PMI and TBS vs. ADD, respectively. It is apparent that neither relationship is linear, and therefore standard least-squares linear regression is not appropriate without transforming the variables first. In both plots, decomposition as measured by TBS first increases quickly in a short amount of time and then levels off in a loglinear fashion.

Calculation of a standard error and confidence intervals for log-linear regressions requires complex algorithms. Transforming the variables can "straighten the curve" and allow for the use of more direct least-squares linear regression. Experimentation with various transformations showed that log-transforming both ADD and PMI and squaring TBS produced the most effective linear regression, taking the form:

$$\text{Log}_{10}(y) = Bx^2 + \text{constant} + \text{error}$$

where B is the slope of the regression line. Figure 6 is a plot of log transformed PMI days against TBS squared and Fig. 7 is a plot of log transformed ADD against TBS squared. Analysis of variance indicates that both regression models are significant ($p < 0.001$) and explain a large proportion of the variation in decomposition. The greater r^2 value for LogADD vs. TBSSQ (0.84) than for LogPMI vs. TBSSQ (0.70) indicates that using ADD should significantly improve the prediction of the time since death because the former measure incorporates both temperature and time. Because we are interested in predicting ADD (the dependent variable) from an observation of body decomposition (TBS, the independent variable), the regression is reversed compared to the previous theoretical relationship given at the beginning of this statistics section. The resulting equation is:

$$\text{Log}_{10}\text{ADD} = 0.002(\text{TBS*TBS}) + 1.81 \pm 388.16$$

or, simplified further:

$$\text{ADD} = 10^{(0.002^*\text{TBS}^*\text{TBS}+1.81)} \pm 388.16$$

where 388.16 is the standard error of the regression in untransformed (non-logged) ADD's. The adjusted r^2 value is 0.845 ($p < 0.001, n = 66$). During the regression analysis, two cases were identified as outliers (Case # 27 and 53 in Table 1). These were removed prior to generating the equation, resulting in a sample size of 66. See the discussion for more about these outlier cases.

To predict the time of death for a new forensic case, one would first calculate the TBS for the individual using the previously-outlined scoring strategy. The TBS (30, in this example) would then be plugged into the simplified equation given above, where $y = \text{ADD}$ and $x = \text{TBS}$:

$$\text{ADD} = 10^{(0.002^*30^*30+1.81)} \pm 388.16$$

$$\text{ADD} = 10^{(1.8+1.81)} \pm 388.16$$

$$\text{ADD} = 10^{(3.61)} \pm 388.16$$

$$\text{ADD} = 4073.81 \pm 388.16$$

One can use the y^x key on a scientific calculator during the last step: enter 10, press (y^x), and enter 3.61. The resulting number

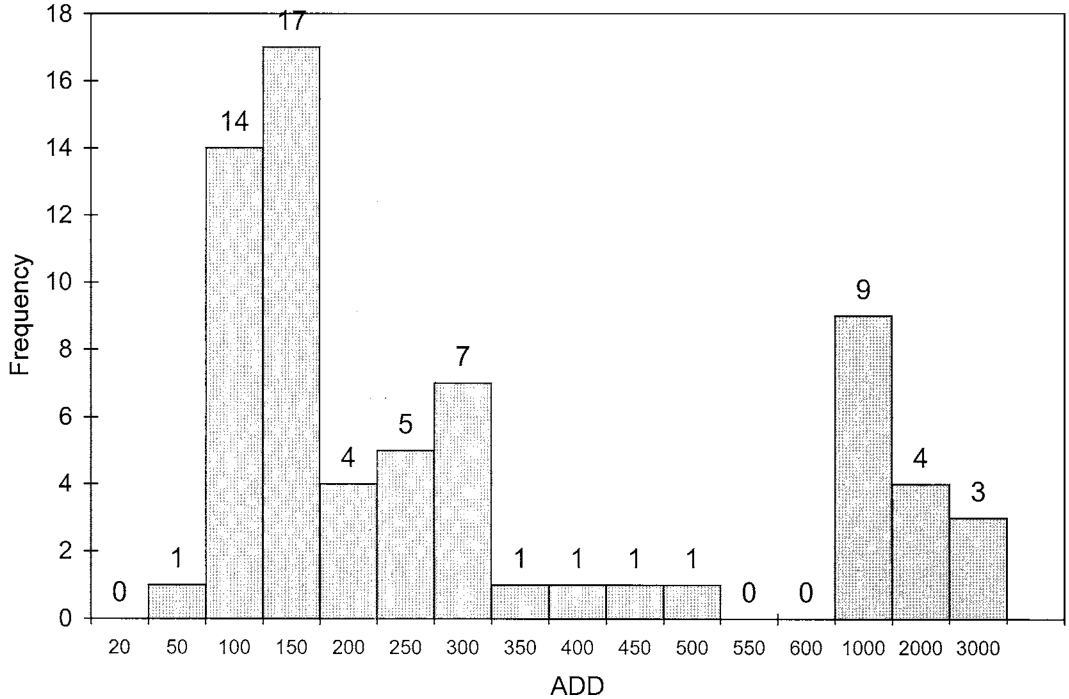

FIG. 3—*Distribution of Cases by Accumulated Degree-days (n = 68).*

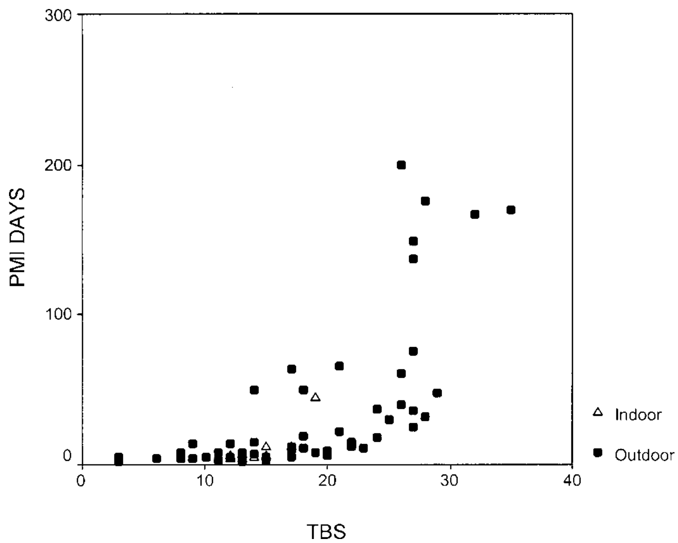

FIG. 4—*Scatter plot of Postmortem Interval vs. Total Body Score (n = 68).*

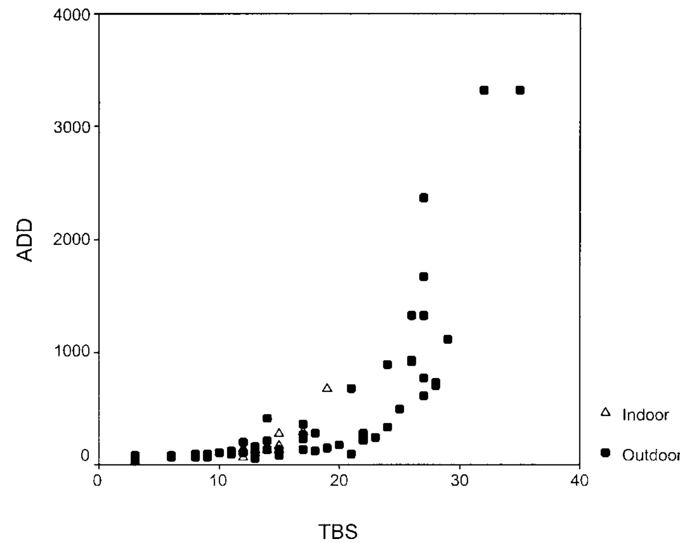

FIG. 5—*Scatter plot of Accumulated Degree-days vs Total Body Score (n = 68).*

(4073.81) is the number of accumulated degree-days that would have been needed for this individual to reach the stage of decomposition observed (TBS = 30). One would then need to obtain local average daily temperatures from a weather station closest to where the individual was found. Treating negative temperatures as 0°C, degree-days would then be added together, working backwards in time from the day of discovery of the remains until the accumulated sum equaled 4073.81. The date of death for the individual would be the day that 4073.81 ADD is reached, after about 68 days of 60°F (15.6°C) weather. The standard error given above can be doubled to approximate the 95% prediction interval for a given TBS:

$$4073.81 \pm 776.32 = 3297.49 \text{ to } 4850.13 \text{ ADDs}$$

Alternatively, a more precise estimate of the 95% prediction interval can be obtained using the following formula:

$$4073.81 \pm 776.32^{*}\sqrt{1.02 + \frac{(\text{TBS} - 17.2)^2}{3522.42}}$$

so for a TBS of 30:

$$4073.81 \pm 776.32^{*}\sqrt{1.02 + \frac{(30 - 17.2)^2}{3522.42}}$$

$$4073.81 \pm 776.32^{*}\sqrt{1.02 + \frac{163.84}{3522.42}}$$

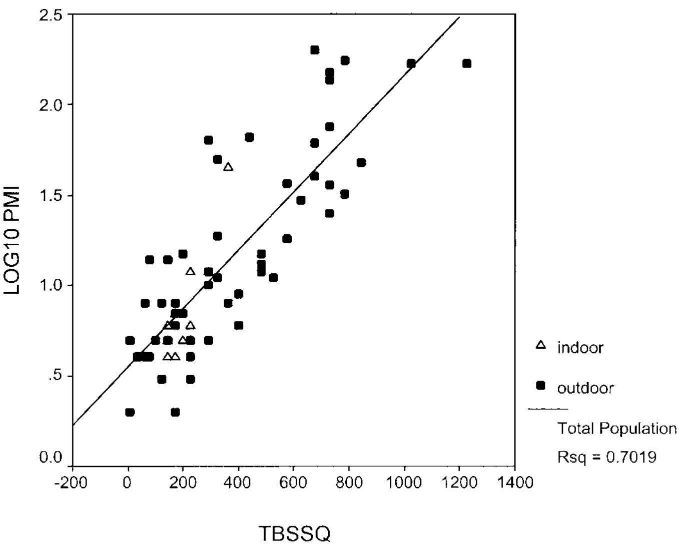

FIG. 6—*Log 10 Transformed PMI vs. TBS squared with Regression (n = 66).*

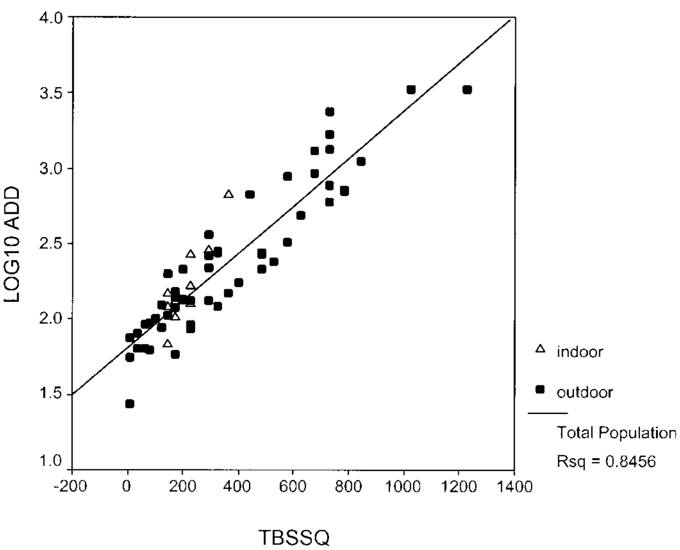

FIG. 7—*Log 10 Transformed ADD vs. TBS squared with Regression (n = 66).*

$$4073.81 \pm 776.32^{*}\sqrt{1.07}$$

$$4073.81 \pm 803.03 = 3270.78 \text{ to } 4876.84 \text{ ADD's}$$

Therefore, one could be 95% certain that the ADD for a body with a TBS score of 30 falls between 3270.78 and 4876.84, or between about 55 and 81 days of 60°F (15.6°C) weather. Note that the true prediction interval is wider than the doubled standard error, and the width of the prediction interval will vary depending on the value of the TBS score, with low and high TBS scores producing a wider prediction interval than midrange TBS scores.

Examination of the 11 indoor cases indicates that they do not stand apart from the outdoor cases in the plots of TBS against PMI or ADD. The data points for the indoor cases are clustered with the majority of the other (outdoor) data points visible in Figs. 4, 5, 6, and 7 and removal of the indoor cases from the regressions does not improve the r^2 values. This finding indicates that the temperature data from outdoors seems to correlate well enough with indoor temperatures in this sample to account for the decomposition that has taken place. However, we must caution that in situations where artificial heating or cooling keeps a room significantly warmer or cooler than outdoor temperatures, it would be very important to calculate ADD from the measured indoor temperature.

Discussion

The major goal of this research has been to apply a more quantitative approach to the estimation of the PMI from decomposing remains. It is clear that decompositional changes can be scored in a way that provides much more information than has been explored by previous researchers. The resulting quasi-continuous values can be subjected to more thorough statistical analysis and can provide more precise and accurate estimates of the PMI. Methods for determining the PMI from decomposition that take into account the temperatures experienced after death produce more accurate estimates of the date of death than those that ignore accumulated temperature.

This study introduces a very different way of looking at the process of soft tissue decomposition. Nearly all previous studies considered decomposition rather typologically, as a process to be described and categorized, not as a continuous process to be scored quantitatively. Many studies seem to consider the changes that occur during decomposition to be too variable or too ambiguous to be of any qualitative use. It is clear that much more can be done to refine our methods of description and analysis of human decomposition.

How practical is a PMI estimate that requires temperature data in order to calculate ADD? Law enforcement agencies will often provide temperature data to specialists working on a human remains case. The National Oceanic and Atmospheric Administration (NOAA) supports a National Climatic Data Center database (http://www.ncdc.noaa.gov) where temperature data is available at low cost for nearly all regions of the United States. In general, the slight inconvenience of obtaining temperature data is worth the increased accuracy of a PMI estimate based on decomposition, particularly if insect evidence was not collected or available.

Most published studies of decomposition do not compare the observed decay stage directly to ADD, so it is difficult to compare results. Vass et al. (13) found that volatile fatty acids (VFA's) under decomposing corpses were no longer detected in the soil after 1285 ADD. VFA's are produced by the decomposition of muscle and fat and Vass concluded that by 1285 ADD all muscle and fat had decomposed, or the remains were essentially skeletonized. By about 1200 ADD all cases had a TBS of greater than 25, which indicates bone exposure over most of the body. Further examination of the data indicates that any TBS over 21 had bone exposure in the limbs, thorax, and head. Since it makes sense that the VFA's finally disappear from the ground somewhat after the last scraps of muscle have decomposed from the bones, the data from this research seems to broadly agree with Vass's findings.

One limitation of the dataset used here is the large gap in ADD between 300 and 600-degree days, with only 4 cases falling in that interval. This gap corresponds to a similar gap in PMI between 80 and 130 days, represented by no cases. In fact, the span from two to 75 days accounts for 91% of the entire sample (62 of 68 cases). This skewed distribution could affect the statistical power of TBS to predict advanced PMIs or ADDs. Future research should focus on obtaining cases with known PMIs ranging between three and twelve months in order to test the equations published here.

Our statistical analysis identified two cases (Case #27 and 53 Table 1) as outliers and these were removed from our predictive equations. Case #27 seems to have higher ADD than would be predicted from the TBS score and perhaps the fluctuating temperatures of late winter in Indiana (freezing at night and warmer during the day) inhibited decomposition while inflating the degree-days during the warm days. Case # 53 is most likely an outlier due to other environmental factors specific to Montana that were not directly controlled for in this study such as altitude or rainfall. Both cases illustrate that it is important to use liberal error ranges and to collect more data in different parts of the country, and during different seasons in order to produce the best equations for each region in the United States.

The model presented here is a retrospective study that illustrates the utility of using decomposition and ADD to estimate the PMI. The decomposition scoring method outlined here should be used cautiously, only on complete, adult-sized remains that have not been burned, buried, or submerged. Variability in decomposition scoring has not been tested with multiple practitioners and this important test should be undertaken prior to widespread use. Future experimental field studies may be useful to control directly for other factors such as sunlight, humidity, rainfall, elevation, vertebrate scavengers, peri/postmortem injuries, and direct recording of scene temperatures. Each of these variables could be measured and analyzed for their effect on decomposition, being incorporated into the regression equation if significant. Researchers are encouraged to test these equations in other climates and use them as an additional tool in consort with other established methods to estimate the PMI. Future research should also concentrate on narrowly defined regions of the United States in order to produce equations that are best tailored to a particular environment. Additionally, further accuracy of this method could be gained testing these equations on a large sample with a precisely known date of death. Although this study used cases from all over the United States, it was biased towards Indiana and Illinois. Practitioners in other parts of the country are encouraged to use the scoring method outlined here to test our equations with their own data or to generate their own equations in order to better track local environmental and climatic conditions. Any application of the equations in unusual circumstances must be treated with great caution. Even under the best of circumstances, one must use a liberal error interval around the estimate.

This pilot study found that over 80% of the observed variation in human decomposition could be accounted for by the combination of elapsed time and temperature as it is reflected in accumulated degree-days. This indicates that decomposition, when scored quantitatively and used to predict ADD, can provide practitioners with a reliable and accurate additional method of estimating the time since death.

Acknowledgments

This research partially fulfilled the requirements for the Masters Degree in Human Biology at the University of Indianapolis, Indianapolis, IN. The authors thank Dr. Nadjib Bouzar (University of Indianapolis) for his help with the statistics, Dr. Christopher Schmidt (University of Indianapolis) for his assistance on this project, and the anonymous reviewers whose comments improved this manuscript. The senior author thanks Dr. Norm Sauer (Michigan State University) for his advice and encouragement and Ryan M. Tubbs (Michigan State University) for her editing skills and support.

References

1. Payne JA. A summer carrion study of the baby pig *Sus scrofa* Linnaeus. Ecology 1965;46:592–602.
2. Reed H. A study of dog carcass communities in Tennessee, with special reference to the insects. Am Mid Nat 1958;59:213–45.
3. Rodriguez WC, Bass WM. Insect activity and its relationship to decay rates of human cadavers in East Tennessee. J Forensic Sci 1983;28:423–32.
4. Micozzi M. Postmortem change in human and animal remains. Springfield, IL: Charles C. Thomas, 1991.
5. Bass WM. Time interval since death: A difficult decision. In: Rathbun TA, Buikstra JE, editors. Human identification. Springfield, IL: Charles C. Thomas, 1984;136–47.
6. Mann R, Bass WM, Meadows L. Time since death and decomposition of the human body: Variables and observations in case and experimental field studies. J Forensic Sci 1990;35:103–11. [PubMed]
7. Bass WM. Outdoor decomposition rates in Tennessee. In: Haglund W, Sorg M, editors. Forensic taphonomy. Boca Raton: CRC Press, 1997;181–6.
8. Sledzik PS. Forensic taphonomy: Postmortem decomposition and decay. In: Reichs KJ, editor. Forensic osteology: Advances in the identification of human remains. Springfield, IL: Charles C. Thomas, 1998;109–19.
9. Willey P, Heilman A. Estimating time since death using plant roots and stems. J Forensic Sci 1987;32:1264–70.
10. Catts E. Analyzing entomological data. In: Catts E, Haskell N, editors. Entomology and death: A procedural guide. Clemson: Joyce's Print Shop, Inc., 1990;124–35.
11. Catts E, Goff M. Forensic entomology in criminal investigations. Ann R Entom 1992;37:253–72.
12. Haskell N, Hall R, Cervenka V, Clark M. On the body: Insects' life stage presence and their postmortem artifacts. In: Haglund W, Sorg M, editors. Forensic taphonomy. Boca Raton: CRC Press, 1997;415–48.
13. Vass AA, Bass WM, Wolt J, Foss J, Ammons J. Time since death determinations of human cadavers using soil solution. J Forensic Sci 1992;37:1236–53. [PubMed]
14. Sabucedo AJ, Furton KG. Estimation of postmortem interval using the protein marker cardiac Troponin I. Forensic Sci Int 2003;134:11–6. [PubMed]
15. Megyesi MS. The effects of temperature on the decomposition rate of human remains. Masters in human biology. Indianapolis: University of Indianapolis, 2001.
16. Galloway A, Birkby WH, Jones AM, Henry TE, Parks BO. Decay rates of human remains in an arid environment. J Forensic Sci 1989;34:607–16. [PubMed]
17. Thew HA. Effect of lime on the decomposition rate of buried remains. Masters in human biology. Indianapolis: University of Indianapolis, 2000.
18. Evans WED. The chemistry of death. Springfield, IL: Charles C. Thomas, 1963.
19. Davidson J. On the relationship between temperature and rate of development of insects at constant temperatures. J Animal Ecol 1944;13:26–38.
20. Kamal A. Comparative study of thirteen species of Sarcoasprophagous, Calliphoridae, and Scarcophagidae (Diptera). Ann Entom Soc Am 1958;51:261–71.
21. Greenberg B. Flies as forensic indicators. J Med Entomol 1991;28:565–77. [PubMed]
22. Higley LG, Haskell NH. Insect development and forensic entomology. In: Byrd JH, Castner JL, editors. Forensic entomology: The utility of arthropods in legal investigations. Boca Raton: CRC Press, 2001;287–302.
23. Archer MS. Rainfall and temperature effects on the decomposition rate of exposed neonatal remains. Science & Justice 2004;44:35–41.
24. Haglund WD, Reay DT, Swindler DR. Canid scavenging/disarticulation sequence of human remains in the Pacific Northwest. J Forensic Sci 1989;34:587–606. [PubMed]
25. Schoenly K, Griest K, Rhine S. An experimental field protocol for investigating the postmortem interval using multidisciplinary indicators. J Forensic Sci 1991;36:1395–1415. [PubMed]
26. Shean BS, Messinger L, Papworth M. Observations of differential decomposition on sun exposed v. shaded pig carrion in coastal Washington State. J Forensic Sci 1993;38:938–49. [PubMed]

Additional information and reprint requests:
Mary S. Megyesi, M.Sc.
Department of Anthropology
354 Baker Hall
Michigan State University
East Lansing, MI 48824-1118
E-mail: megyesim@msu.edu