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Multiple-Probe Thermography for Estimating the Postmortem Interval: I. Continuous Monitoring and Data Analysis of Brain, Liver, Rectal and Environmental Temperatures in 117 Forensic Cases

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ABSTRACT: One hundred seventeen forensic postmortem cases have been studied under controlled conditions. In each case, temperatures of the brain, liver, rectum, and the environment were monitored over a period beginning shortly after death and ending up to 60 h postmortem. The four temperature measurements were recorded every 5 to 10 min using the Microwave Thermography System. Rectal and environmental temperatures were measured by electrical thermocouples while brain and liver temperatures were measured using microwave probes. Data acquisition, analogue-to-digital conversion (ADC), and data processing were provided by a microcomputer. The ADC technique is described and its problems are discussed. The data were then transferred to a mainframe computer for extensive curve-fitting and statistical analysis. The microcomputer-based ADC and data logging and acquisition were found to be accurate, fast, easy to implement, and useful for the field. The postmortem rate of human body cooling was found to be adequately represented by triple-exponential equations.

KEYWORDS: forensic science, forensic pathology, forensic medicine, postmortem cooling, time of death, postmortem interval, microwave thermograph, curve fitting

The estimation of the time of death is often crucial to the outcome of forensic cases, especially in homicides (1–4). In the literature, many factors affecting the postmortem drop in body temperature are discussed and it is now apparent that the overall picture is rather complicated. Accordingly, simple models are intrinsically insufficient and the mathematical complexity of more sophisticated models or formulae should not be a restriction on their use in practice, whenever such models or formulae can offer improvements in the estimation of the postmortem interval (PMI). This is particularly true today when almost every discipline has been partially or totally affected by the computer, which makes it easy, in practice, to use even the most complicated formulae.

Experimental

Conditions of Temperature Monitoring

In this study, the Microwave Thermography System (a device recently developed at the University of Glasgow by one of the authors, DDL) was used for postmortem temperature measurements (1). In summary, it consisted of: two microwave radio aerials or sensors (microwave probes), a microwave radio-receiver unit, two digital pyrometers fitted with rigid electrical thermocouples, and an electronic data logger compatible with a chart-recorder and microcomputer with an in-built analogue-to-digital converter (ADC). The microwave probes were used to monitor the brain and liver temperatures while the thermocouples were used to monitor the rectal and environmental temperatures.

The work described in this study was carried out in the Glasgow City Mortuary during the years 1983–1986. The experiments were performed in a room, approximately 5 m by 4 m by 3.5 m, which had one window, about 3 m by 2 m, with no blinds. The window was kept closed at all times. The room was usually illuminated by daylight or fluorescent light but not by direct sunlight. It had one door, which was closed except to permit occasional entry and exit. There was no significant air movement in the room. The room temperature was not regulated so that some of the actual conditions at the field could be simulated. Legal and ethical requirements were fulfilled.

The body was conveyed to the mortuary by ambulance and was divested in the reception room. Temperature measurements were started immediately. The cases were selected according to the following criteria:

1. The exact time of death should be known to within 15 min.
2. The elapsed time between death and the arrival of the body in the mortuary should be as short as possible, preferably less than 45 min, so that the body should feel quite warm to the touch.
3. The circumstances of the death should allow the body to be kept, undisturbed, at the mortuary for a period of at least 20 to 36 h, preferably up to 60 h or more, to allow many hours of

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monitoring. In practice, this criterion meant that cases were restricted to those for which the cause of death was either natural or nonsuspicious.

On arrival of a case satisfying the above criteria, the body was accurately weighed using a weighing trolley, its crown-sole length (height) was measured with an autopsy ruler, and the circumference of the head and the width of the hip were then obtained with a tape measure. Information concerning the name, sex, body measurements, the exact time of death, and the time of beginning and end of monitoring were recorded. The causes of death were obtained from the death certificates or the medico-legal necropsy reports.

The body was laid in a supine position, with legs together and arms by the side, on a metal-topped hospital trolley, which was covered by a plastic sheet. The body was either monitored naked or covered with two cotton blankets. In the latter case, a third blanket was placed on the trolley beneath the body. In this group the liver probe was left uncovered and was placed in contact with the body through small holes in the blankets. Thus, two body groups were studied: naked and covered body groups.

The temperatures of three body sites, namely, the brain, liver, and the rectum were monitored, as well as the temperature of the environment. During monitoring, the microwave probes were placed in contact with the skin of one of the temporal regions and of the right hypochondrium, to monitor the temperature of the brain and the liver, respectively (1).

Occasionally, a pathologist, police officer, or family doctor accessed the body for the purpose of identification prior to issuing a death certificate. This was mostly carried out without interruption of the temperature monitoring and with as little disturbance as possible. If, for any reason, the monitoring was interrupted for any length of time, the case would be excluded from further analysis.

Data Logging and Statistical Analysis

Analogue to digital (AD) conversion of the signals from the microwave receiver and pyrometers was carried out using a microcomputer (1), which has an in-built 12-bit analogue-to-digital converter (ADC). The resolution of the ADC was 0.6 mV corresponding to 1°C. Each input channel took only 10 ms to convert an input voltage to a digital value. It was therefore possible to average a large number of converted values before storing the readings: an average of 300 values was taken in approximately 12 s. The reproducibility of the AD conversion was examined by applying a constant voltage to one channel and comparing the average digital values returned. The linearity and accuracy of the ADC were tested by applying calibrated voltages and plotting these versus the digital values returned.

Temperature data from four channels were recorded along with time scale provided by the microcomputer. Plots of the raw temperature data versus time were performed and visualized on a monitor screen, to assess their uniformity and validity for further processing and analysis. Artifacts such as electrical spikes were revealed and corrected by editing the file to remove the aberrant data and irremediably bad traces were excluded (1). An important function, i.e., the temperature difference ratio, was calculated for successive postmortem intervals. This was computed according to this equation:

$$R = \frac{(T_{bt} - T_{et})}{(T_{b0} - T_{et})} \tag{1}$$

where:

T_{bt} = temperature at any body site measured at any given time t
T_{b0} = temperature of any body site at the moment of death as established below, i.e., Constant (2,3)
T_{et} = temperature of environment measured at time t
R = temperature difference ratio

The extrapolation method used to calculate the temperature of each body site at the moment of death (T_{b0}) was outlined previously (2,3). In summary, temperature data for the first three hours of each body site were fitted using single exponential equations. The fitted curve was extrapolated backwards to obtain the intercept on the Y-axis (i.e., the temperature axis). This is considered to be the temperature at the moment of death.

Following initial processing, curve fitting procedures of the values of temperature difference ratio, R, versus postmortem interval, t, were carried out using the Biomedical Data Program (BMDP). To obtain the optimum fit for each curve, equations involving two, three, and four exponential functions were compared. The formulae containing three exponential functions is given by Eq 2:

$$R = P_1e^{P_2t} + P_3e^{P_4t} + P_5e^{P_6t} \tag{2}$$

where R = temperature difference ratio (Eq 1). P_1 to P_6 are parameters empirically derived in this study, i.e., Constants (See Part II) and t is the time after death in hours.

Results

The values returned by the ADC were found to have good linear relationship with the converted voltages as measured by the voltmeter. During the period of the study, 128 cases were collected. After the initial data processing, 11 cases were found not to be useful for further analysis and were excluded due to faults in the recording, interruption of monitoring, or irregularities in the traces as a result of artifacts or electrical noise (spikes). The results described here represent the study of 117 cases, including 74 cases (63%) monitored as naked bodies and 43 cases (37%) monitored as covered bodies. Several body parameters were measured. These include the age, weight, height, and the circumferences of the head and the hip (Table 1). The causes of death in all cases studied were natural.

TABLE 1—*Characteristics of cases studied (*N *= 117).*

Item	Age (Years)	Hip Circumference (m)	Head Circumference (m)	Weight (Kg)	Height (m)
Range	30–85	0.76–1.19	0.46–0.71	42–117	1.52–1.98
Mean	63.4	0.997	0.57	70.5	1.74
S.D.	13.4	0.095	0.057	0.098	0.098

TABLE 2—*Distribution of monitoring periods (hours) and time interval elapsed between death and the beginning of monitoring in the cases studied,* N *= Number, % = Percent.*

Monitoring Period (Hours) Mean = 30.25, S.D. = 12.7							PM Interval before Monitoring (minutes) Mean = 32, S.D. = 15		
	Naked		Covered		Total				
Range (hours)	N	%	N	%	N	%	Range (minutes)	N	%
0–5	2	1.7	0	0	2	1.7	0–14	0	0
6–10	1	0.9	0	0	1	0.9	15–29	35	29.9
11–15	3	2.6	0	0	3	2.6	30–44	39	33.3
16–20	11	9.4	3	2.6	14	12.0	45–59	16	13.7
21–25	20	17.1	17	14.5	37	31.6	60–74	14	12.0
26–30	10	8.5	9	7.7	19	16.2	75–89	4	3.4
31–35	5	4.3	4	3.4	9	7.7	90–104	3	2.6
36–40	4	3.4	0	0	4	3.4	105–120	2	1.7
41–45	4	3.4	7	6	11	9.4	121–135	1	0.9
46–50	6	5.1	2	1.7	8	6.8	136–150	1	0.9
51–55	1	0.9	0	0	1	0.9	151–165	0	0
56–60	7	6	1	0.9	8	6.8	166–180	2	1.7
Total 6–60	74	63.3	43	36.7	117	100	Total 15–180	117	100

The monitoring periods ranged from 2.5 to 60 h with an average value of 30.25 h (Table 2). The distribution of monitoring periods in naked and covered bodies was almost identical. As to the postmortem intervals between death and the start of monitoring most cases (74 cases or 63.3%) were aggregated in the region from 15 to 45 min (Table 2).

Environmental temperatures under which monitoring was carried out ranged from 8.38 to 22.76°C. The average value was 15.2 ± 3.2 °C.

Primary data reduction was satisfactorily carried out to produce, for instance, plots of temperature of three body sites versus time (Fig. 1) and temperature difference ratio (Eq 2) for each body site versus time. When the values of the temperature difference ratio (*R*) of each case were curve-fitted, over the whole monitoring period, using equations containing two, three, and four exponential terms, the best fit was found to be given by the triple-exponential formula (Eq 2, Fig. 2). Average values of (*R*)

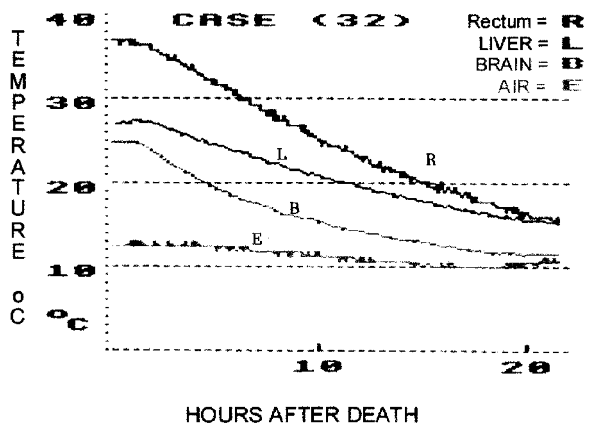

FIG. 1—*Typical plots of rectal* R, *liver* L, *brain* B *and environmental E temperatures versus postmortem interval in hours.*

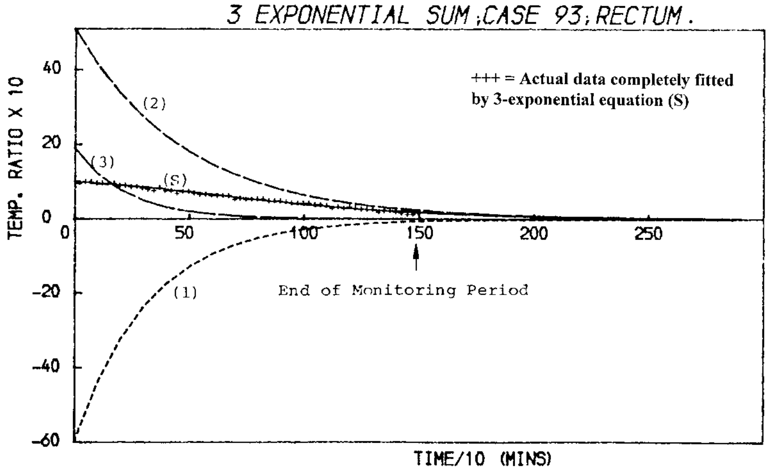

FIG. 2—*Example of rectal cooling curve fitted by a sum* (S) *of 3-exponential terms (1–3) for a case in the covered body group.*

TABLE 3—*Average temperature difference ratios for the cases studied* (N $= 117$). *Brain is not affected by covering of the torso.* T_{b0} *= temperatures of body sites at the moment of death found in this study and used as constants [*T_{b0} *for brain and liver are low because of the microwave attenuation (1)].*

	Covered Body Group ($N = 43$)						Naked Body Group ($N = 74$)			
	Rectum ($T_{b0} = 32.2$°C)		Liver ($T_{b0} = 32.7$°C)		Brain ($T_{b0} = 27.7$°C)		Rectum ($T_{b0} = 36.6$°C)		Liver ($T_{b0} = 27.5$°C)	
Postmortem Interval	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
0.0	1	0	1	0	1	0	1	0	1	0
0.5	0.97	0.019	0.99	0.012	0.94	0.029	0.96	0.017	0.96	0.018
1.0	0.94	0.026	0.98	0.022	0.88	0.052	0.93	0.037	0.92	0.034
1.5	0.91	0.047	0.96	0.031	0.82	0.07	0.89	0.046	0.88	0.046
2	0.89	0.057	0.95	0.041	0.77	0.085	0.863	0.066	0.84	0.058
4	0.80	0.084	0.90	0.067	0.59	0.13	0.75	0.109	0.72	0.089
6	0.72	0.097	0.86	0.085	0.45	0.152	0.645	0.13	0.62	0.106
8	0.65	0.104	0.81	0.098	0.34	0.165	0.54	0.14	0.53	0.113
10	0.58	0.11	0.76	0.108	0.25	0.168	0.45	0.412	0.46	0.116
12	0.51	0.11	0.71	0.115	0.19	0.164	0.367	0.14	0.40	0.117
14	0.45	0.11	0.67	0.13	0.18	0.15	0.30	0.13	0.35	0.116
16	0.40	0.11	0.61	0.13	0.15	0.15	0.247	0.074	…	…
18	0.35	0.11	0.56	0.13	0.12	0.14	0.204	0.066	0.27	0.113
20	0.30	0.107	0.52	0.13	0.097	0.14	0.16	0.1	0.23	0.11
22	0.26	0.108	0.45	0.15	0.078	0.14	0.14	0.05	0.2	0.11
24	0.22	0.102	0.44	0.13	0.06	0.13	0.10	0.082	0.176	0.107
28	0.16	0.09	0.36	0.12	…	…	0.081	0.03	0.134	0.103
32	0.12	0.08	0.30	0.12	…	…	0.037	0.05	0.10	0.10
36	0.086	0.07	0.25	0.11	…	…	0.021	0.04	0.08	0.09
40	0.06	0.06	0.20	0.104	…	…	0.015	0.029	0.06	0.09
50	0.03	0.04	0.12	0.084	0.08	0.13	0.006	0.015	0.028	0.077

versus selected successive postmortem intervals are shown in Table 3.

Discussion

Studying Protocol

There has been some controversy in the literature concerning the conditions under which studies of postmortem cooling should be conducted. Some authors have suggested that controlled conditions are not relevant to the actual situation in the field. However, our view is that if the problem is to be approached systematically, the postmortem drop in body temperature should only be studied under controlled conditions. It is impossible to interpret results from studies of randomly selected cases, whereas it is more practicable to study the problem under different sets of controlled conditions which are likely to be met in practice. Some researchers, on the contrary, concentrated on purely nonbiological experimental models, which were constructed to simulate the human body (5). Such theoretical studies and experimental models are obviously of great importance, however, their practical usefulness is limited.

The cases used in the present study were chosen to satisfy the criteria given earlier. First, the death should be due to natural causes: this had the twin advantages that the body was not urgently needed for necropsy nor was it involved in medico-legal investigations normally required in suspicious death. In most cases, the cause of death was heart disease, reflecting its high incidence in the Glasgow area. Death involving hyper- or hypothermia was excluded to avoid wide variation of the body temperature at the moment of death. Second, the cases investigated in this research were demographically typical of the population norm except that there were no children among them. Despite that, the age groups studied covered those most likely to be involved in real practice.

The initial movement of the body from the locus of death to the experimental room in the mortuary was inevitable not only because it was difficult to monitor body temperature at the locus, but also because our plan was to study the problem under controlled conditions. It is obvious that the study room conditions could more easily be controlled. Apart from this initial transfer and the movement during divestment of clothes, the body was kept undisturbed, in most cases, throughout the whole course of the monitoring period. All bodies were laid in a supine position in the manner described earlier, so that the effect of posture on cooling was uniform. The bodies were monitored either naked or covered because these two situations are the most likely to be met in practice. In all covered bodies the amount of covering was kept the same, therefore the effect of this factor was also controlled.

Monitoring was started as soon as possible after death, mostly within 45 min postmortem so that the initial stage of cooling was examined (Table 2), which is the most critical and controversial of all stages of postmortem cooling. However, it was difficult to find cases to satisfy this condition, so restricting the number of the cases collected. It was also important to study the problem of postmortem cooling for a long time after death. This is because most suspicious cases in forensic practice, where timing of death is likely to be required, are not discovered shortly after death. In this study monitoring was continued for as long as possible, preferably up to 60 h after death (Table 2). Where possible, monitoring was continued for at least 30 h, at which point the temperature difference between the body and the environment was less than a few degrees and a practical limit was imposed by the precision of the device used (1°C).

In each case, additional body measurements were collected including the head circumference, the width of the hip, the weight, and the height (Table 1). These were to establish which factors have significant effects on the cooling rate (2–4).

This study was conducted under a wide range of environmental temperatures, so that the effects of cold and moderately warm weather were studied. However, it was not possible to study the effect of the environmental humidity and air movement on cooling and all cases were studied under practically stagnant air.

Site of Temperature Measurements

It is generally accepted that in any study of the postmortem rate of cooling, the temperature to be measured is that of the "inner core" of the body (6). However, several investigators have shown that, in life and even under resting conditions, temperature differences exist between central regions of the body (i.e., the human body is not thermally thin) (7). Therefore concepts such as body "core," "critical tissue," and a "single representative measurement of body temperature" have been questioned (7,8).

In general the rectum has been found to be the slowest to respond to heating or cooling processes (7,9,10–14) and there is evidence that the brain (more correctly, the central part of the brain) responds most quickly (11,15). On the other hand, the liver responds more quickly than the rectum but still more slowly than central parts of the body (7,10,16). As a result of these studies, increasing doubt has been cast on the reliability of the rectal temperature in reflecting the actual temperature of the body. It has been suggested that if the main concern is the rate of change of body temperature, rectal temperature will be less suitable than most other sites (5,7,13,14,18–20). In life, the rectal temperature in man is one of the highest temperatures in the "body core." The exact reason for this is not known, but it is believed to be anatomical (15). A further difficulty associated with the rectal temperature is the variation due to the position of the sensing element in the rectum (7,13). Mead et al. have found that the rectal temperature, measured 8 in. from the external anal sphincter, was almost always lower than temperatures recorded at intermediate points along the rectum. Also, they encountered some technical difficulties in positioning the sensing element in the rectum and suggested the use of a rigid thermocouple rather than the catheter type so that depth of penetration and position could be adjusted more easily (13). Many researchers have pointed out that the rectum is not positioned in the center of the body, and Hiraiwa et al. have shown by Computer Tomography (CT) scanning that the rectum is placed near to the junction of the anterior three-quarters and the posterior quarter inside the body (5,19,21).

In summary, temperature measurements of other regions such as the brain and the liver are considered preferable to those recorded in the rectum. Nevertheless, most temperature-based methods for the time of death, so far, have been based on temperature measurements in the rectum and few studies have been carried out on the postmortem temperature drop of the brain or liver. This is mainly because there is no easy way to access these organs. A thermometer or electrical thermocouple has to be introduced through a puncture wound in the abdomen (22,23) or one of the eyes (24) unless a hole is drilled in the skull. This may not only be ethically unacceptable but also may affect the actual cooling process. Using the Microwave Thermography System, it is now possible to take the temperature of these and other organs by a noninvasive and ethically acceptable method (1). Since microwave thermography was used for the first time in postmortem temperature measurements in this study, it was necessary to include a traditional method of temperature measurement after death as a control. The obvious choice was to monitor the rectal temperature using an electrical thermocouple. In this study a rigid thermocouple of a sufficient length was used so that its depth and position could be adjusted in each case.

Several authors have anticipated that temperature measurements of the brain would yield valuable information (20–25). The theoretical basis for this expectation may be summarized as follows. First, the shape of the head is approximately globular. Second, there are only slight individual variations in the size of the head. Third, the clothing of the body, apart from a head covering, if any, plays no role. Fourth, the amount of hair, however, varies, but in area covered as opposed to length. Lastly, the center of the brain is rather uniformly insulated by brain tissue and cerebrospinal fluid (24). Lyle and Cleveland found that the temperature fall in the brain showed the least individual variation (21) and Naeve and Apel concluded that the measurement of the brain temperature was the most useful of all temperature measurements (25).

Body Temperature at the Moment of Death

The need to know the body temperature at the moment of death is a prominent drawback in all methods that depend on the rate of cooling for estimating the postmortem interval (2–5,22,24,26,27). In this study, temperatures of the brain, liver, and rectum at the moment of death were estimated using the data collected during the first 3 h of the monitoring period by extrapolating backwards. This has twin advantages: first, problems due to variation between one measuring device and another were avoided by this approach, particularly with respect to microwave attenuation by tissues, which resulted in artificially low temperature readings (1); second, when the time of death is estimated using the formulae devised in our study (Part II), there is no longer a need to assume the temperature at the moment of death. This is rather used as one of the constants incorporated in the formulae. The average values of the temperatures of the three body sites at the moment of death T_{b0} were published previously (2,3).

Acquisition and Analogue Recording

In this study, analogue signals from the microwave receiver and the pyrometers were converted to digital form (AD conversion) by a 12-bit ADC contained in the microcomputer. An important feature of this ADC was its ability to handle up to four channels of input (28), used for the temperatures of the brain, liver, rectum, and the environment.

With any ADC there is a possibility that the returned value may be inaccurate because of manufacturing tolerance in the resistors of the voltage divider (28). This problem can easily be overcome by implementing an adjustment or a correction factor into the program used for conversion. One way for performing this is to apply known voltages and calculate the factor for correcting the output values on the assumption that these voltages are accurately known. For the purpose of this work, a similar test was carried out and the returned digital output value was found to be in a good linear relationship with the converted voltages. This meant that there was no need to implement a correction factor into the AD conversion program. Another problem of the ADC is the possibility of small random errors in the ADC reading (28). For this reason it is advisable that a given voltage, which is to be converted, should be read several times and an average of these readings should be taken. In this study each signal, i.e., each datum, was read 300 times before an average returned digital value was stored. This was possible because each input channel took only 10 ms to convert an input voltage to a digital value. Although manual digitization was easy and accurate, AD conversion by ADC was preferable.

Data Processing

A trace was considered irremediable either because it was interrupted or because it contained too many electrical artifacts "spikes" (1). Several types of data reduction were performed. These involved, for example, plots of temperature versus time, which were usually carried out to check that the correction of the data file had been performed accurately. Other examples are plots of temperature difference ratio versus time.

Temperature difference ratios (Eq 2) are used in preference to simple temperature measurements in all stages of data analysis. This is because first, these ratios are required for the Infinite Cylinder Model, i.e., the triple-exponential equation (29) and second, the temperature difference between the body and the environment is the most important of all factors that influence postmortem body cooling. Third, using these ratios can probably minimize the possible errors, which may result from fluctuations of environmental temperature during the period of body cooling. It is important to note that in the version of the Infinite Cylinder Equation used in this work, it is assumed that the environmental temperature at the moment of death is equal to the temperature of the environment at the time when monitoring is started. However, in most cases in this study, there were, in fact, differences between the temperature of the locus of death and that of the experimental room. These small changes in environmental temperatures may have either very small or no effect on the cooling behavior. This has been shown to be true by some authors (19,30).

Some of the inferences made from the primary analysis of the data were given earlier (1–4). It was concluded that: first, the postmortem cooling was a complicated phenomenon, which could not be described by a simple procedure or model; second, the best description of the postmortem cooling curve was obtained by triple-exponential equations; third, there were major differences between body sites with respect to the rate of postmortem cooling; fourth, cooling of covered and naked bodies was also different, particularly for the liver and the rectum; fifth, there were considerable individual variations in the rate of cooling of a given body site; and sixth, despite these variations there were common characteristics of postmortem cooling of each body site for the covered and naked groups.

The aim of the next article is to find these common aspects and put them in a manner that could be used practically in the field.

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