Int J Legal Med (2007) 121: 267–273
DOI 10.1007/s00414-006-0088-8

ORIGINAL ARTICLE

Yoshimasa Kanawaku · Jun Kanetake · Atsuki Komiya ·
Shigenao Maruyama · Masato Funayama

Effects of rounding errors on postmortem temperature measurements caused by thermometer resolution

Received: 12 August 2005 / Accepted: 2 March 2006 / Published online: 25 April 2006

Abstract Beginning 7 h after death, a datalogger was used to measure the temperature in the external auditory canal of an adult male body placed in a refrigerated room. The sequence of measured values approximated a single exponential function with a correlation coefficient of 0.998475. This suggests that the starting time of body cooling in the refrigerated room under constant temperature can be calculated with less error using any two data points recorded by the datalogger. However, the results of such calculations varied widely and longer postmortem intervals demonstrated greater calculation errors. Periodic errors also appeared. Mathematical simulations showed that this variation was caused by rounding errors, which represent the difference between the thermometer readings and the true temperature. The resolution of the thermometer was 0.1°C, a normal specification; however, even this led to noticeable rounding errors. Therefore, significant errors may influence postmortem interval estimations using other body temperatures. When body temperatures are used to determine the time of death, a method that minimizes rounding errors should be considered.

Keywords Postmortem interval · Time of death · Postmortem cooling · Resolution · Rounding error

Y. Kanawaku (✉) · J. Kanetake · M. Funayama
Division of Forensic Medicine,
Department of Public Health and Forensic Medicine,
Tohoku University School of Medicine,
Sendai, 980-8575, Japan
e-mail: ykanawaku@nifty.com
Tel.: +81-22-7178110
Fax: +81-22-7178112

A. Komiya · S. Maruyama
Institute of Fluid Science, Tohoku University,
Sendai, Japan

Introduction

Many forensic pathologists use a body temperature method based on postmortem cooling to estimate the time of death. There have been many reports about errors in the death time estimation [1–10]. However, there have only been few reports on rounding errors caused by the resolution of the thermometer. In this report, we continuously and automatically recorded postmortem temperature in the external auditory canal at 1-min intervals for 17 h at an air temperature of 4°C to analyze the influence of rounding errors. In addition, we simulated postmortem body temperatures while considering rounding errors in the true temperature.

Mathematical models for analysis

Equation governing postmortem cooling in the external auditory canal

It is likely that the temperature in the external auditory canal will decrease rapidly after death at cold ambient temperature because the depth of the canal is shallow compared with the radius of the head. Therefore, the equation governing postmortem cooling in the canal is given by the following equation using the Newtonian model [11, 12]:

$$-MS\frac{dT}{dt} = hA(T - T_e) \tag{1}$$

where M, S, t, T, T_e, h, and A are the mass of the body, the specific heat of the body, time, the temperature of the external auditory canal, the environmental temperature, the heat transfer coefficient from the surface to the environment, and the surface area, respectively.

Assuming that the environmental temperature does not change with time and integrating Eq. 1, the following equation is obtained:

$$T = (T_0 - T_e)e^{-Zt} + T_e. \tag{2}$$

where T_0 and Z are the temperature of the canal at the initial time and the cooling factor (=hA/MS), respectively.

To simplify the mathematical handling, Eq. 2 can be converted as follows:

$$\theta = \frac{T - T_e}{T_0 - T_e} = e^{-Zt}. \tag{3}$$

where θ is the nondimensionalized temperature ($0 \leq \theta \leq 1$).

Setting θ=1 at t_0 and taking the logarithm of both sides, the following equation is obtained:

$$\ln \theta = -Z \cdot t. \tag{4}$$

Equations for estimating the cooling interval

At a given time, t_1, during the cooling process, θ is θ_{t_1}.

$$\ln \theta_{t_1} = -Z \cdot t_1. \tag{5}$$

Furthermore, θ at Δt from t_1, is $\theta_{t_1+\Delta t}$

$$\ln \theta_{t_1} +_{\Delta t} = -Z \cdot (t_1 + \Delta t). \tag{6}$$

Substituting Eq. 5 into Eq. 6 and solving for t_1, the following equation is obtained:

$$t_1 = \frac{\Delta t}{\ln \theta_{t_1+\Delta t} - \ln \theta_{t_1}} \cdot \ln \theta_{t_1}. \tag{7}$$

If the start time of cooling is calculated from more than two measured results, the estimation formula can be derived using a least squares method [13]. Concretely, from n measured results ($\ln\theta_1$, t_1), ($\ln\theta_2$, t_2), ..., ($\ln\theta_n$, t_n), the equation of postmortem cooling in the canal can be regressed as follows:

$$\ln \theta = \frac{n\sum(t_k - t_1)\ln\theta_k - \left(\sum(t_k - t_1)\right)\left(\sum \ln\theta_k\right)}{n\sum(t_k - t_1)^2 - \left(\sum(t_k - t_1)\right)^2} \cdot t + \frac{\sum(t_k - t_1)^2 \sum \ln\theta_k - \sum(t_k - t_1)\ln\theta_k \sum(t_k - t_1)}{n\sum(t_k - t_1)^2 - \left(\sum(t_k - t_1)\right)^2}. \tag{8}$$

We must subtract t_1 from each value of t_k in the regression line because t_1 is unknown in the real case and only the time intervals from the first measurement point can be seen. Strictly, the estimated cooling intervals are not the t_1 but the intercept on the time axis of Eq. 8, t'.

Therefore, substituting t=t' and $\ln\theta$=0 into Eq. 8 and rearranging the equation, the following generalized formula for estimation of cooling interval of the canal is obtained.

$$t' = -\frac{\sum(t_k - t_1)^2 \sum \ln\theta_k - \sum(t_k - t_1)\ln\theta_k \sum(t_k - t_1)}{n\sum(t_k - t_1)\ln\theta_k - \left(\sum(t_k - t_1)\right)\left(\sum \ln\theta_k\right)} \tag{9}$$

Materials and methods

Case subject

The subject was a 52-year-old male who collapsed suddenly at work and was subsequently taken to a clinic but did not respond to cardiopulmonary resuscitation. He was transported to an autopsy room and stored in a naked supine position on a stainless steel stand in a refrigerated room at an air temperature of 4°C. The temperature in the left external auditory canal was measured at 1-min intervals using a temperature datalogger TR-71U (T&D corporation, Japan) and sensor TR-1106 Teflon-Shielded Sensor (T&D corporation) for 17 h, beginning 7 h after death. The resolution of the thermometer was 0.1°C. The thermometer

Table 1 Measurement conditions in the subject case and the simulation cases

Fig.	Temperature	Assumed measurement conditions				Applied estimation formula
		Measurement number	Measurement interval [min]	Thermometer characteristics		
				Resolution [°C]	Accuracy [°C]	
1a	Measured temperature	2	30	0.1	±0.5	Eq. (7)
1b		30	1			Eq. (9)
2a	Rounded true temperature	2	30	0.1	±0	Eq. (7)
2b		2	60	0.1		Eq. (7)
2c		30	1	0.1		Eq. (9)
2d		2	30	0.01		Eq. (7)
3	Rounded true and measured temperature	2	30	0.1	±0.±0.5	Eq. (7)

probe was inserted into the auditory canal and fixed with adhesive tape to maintain the position at a depth of about 3 cm. All results were nondimensionalized and transformed into logarithms, then regressed as a straight line. Cooling intervals in the refrigerated room were then estimated using Eqs. 7 and 9, and the estimated to actual ratios were determined.

Simulation of postmortem cooling

In simulations to study rounding errors, we defined the values represented by the aforementioned approximate line as the true temperatures. True temperatures were computed every minute. To transform these true temperatures into measurement readings, they were rounded off in accordance with the thermometer resolution. The cooling intervals in the refrigerated room were estimated using Eqs. 7 and 9 under various measurement conditions (Table 1) and the ratios of the estimated cooling to actual cooling intervals were calculated. All analyses were then conducted using Microsoft Office Excel 2002.

Results

Case subject

In this case, the environmental temperature, T_e, was defined as the arithmetic mean air temperature (3.129°C) from 60 to 1,020 min, and T_0 was set at 30.8°C. Making all measured results into nondimensional values and regressing them as a single exponential function, the following equation is obtained:

$$\theta = 1.00944e^{-0.00211048 \cdot t}. \tag{10}$$

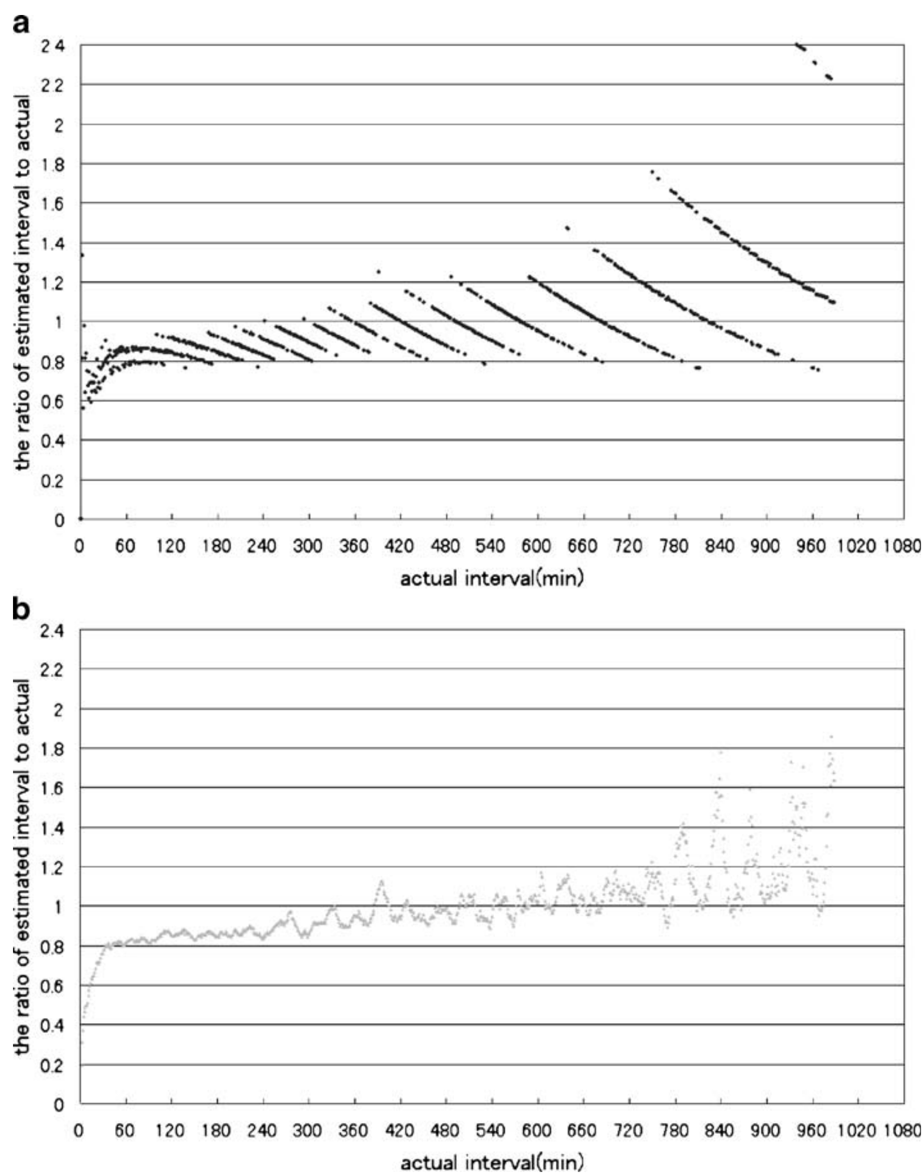


Fig. 1 Ratio of estimated to actual cooling intervals for this case. **a** Two temperatures at an interval of 30 min, **b** 30 temperatures at intervals of 1 min

The correlation coefficient of Eq. 10 is 0.998475, suggesting the validity of this single exponential function as a representation of postmortem cooling in the refrigerated room. By computing the regression line of the logarithm-transformed dimensionless measured results, the following linear equation is obtained:

$$\log \theta = -0.00211048 \cdot t + 0.00940040 \qquad (11)$$

The correlation coefficient of Eq. 11 is the same as that of Eq. 10.

Figure 1a demonstrates the ratios of the estimated cooling intervals to the actual cooling intervals. The estimated intervals were calculated using Eq. 7 and two temperatures at intervals of 30 min, while the actual intervals were taken as the first of these two temperatures. For example, using the temperatures at 391 and 421 min, the estimated time interval was calculated to be 489 min. In this case, the actual time was 391 min and the ratio was 1.25(489/391). Figure 1b demonstrates the ratios of 30 temperatures at intervals of 1 min.

Postmortem cooling simulations

Simulation results are shown in Fig. 2a–d according to the conditions shown in Table 1. Additionally, Fig. 3 shows a superimposition of Figs. 1a and 2a and the results suggest that the error pattern shown in Fig. 1a is remarkably similar to that in Fig. 2a.

Discussion

The measured values approximated a single exponential function with a correlation coefficient of approximately 0.998475. This suggests that the starting time of cooling in

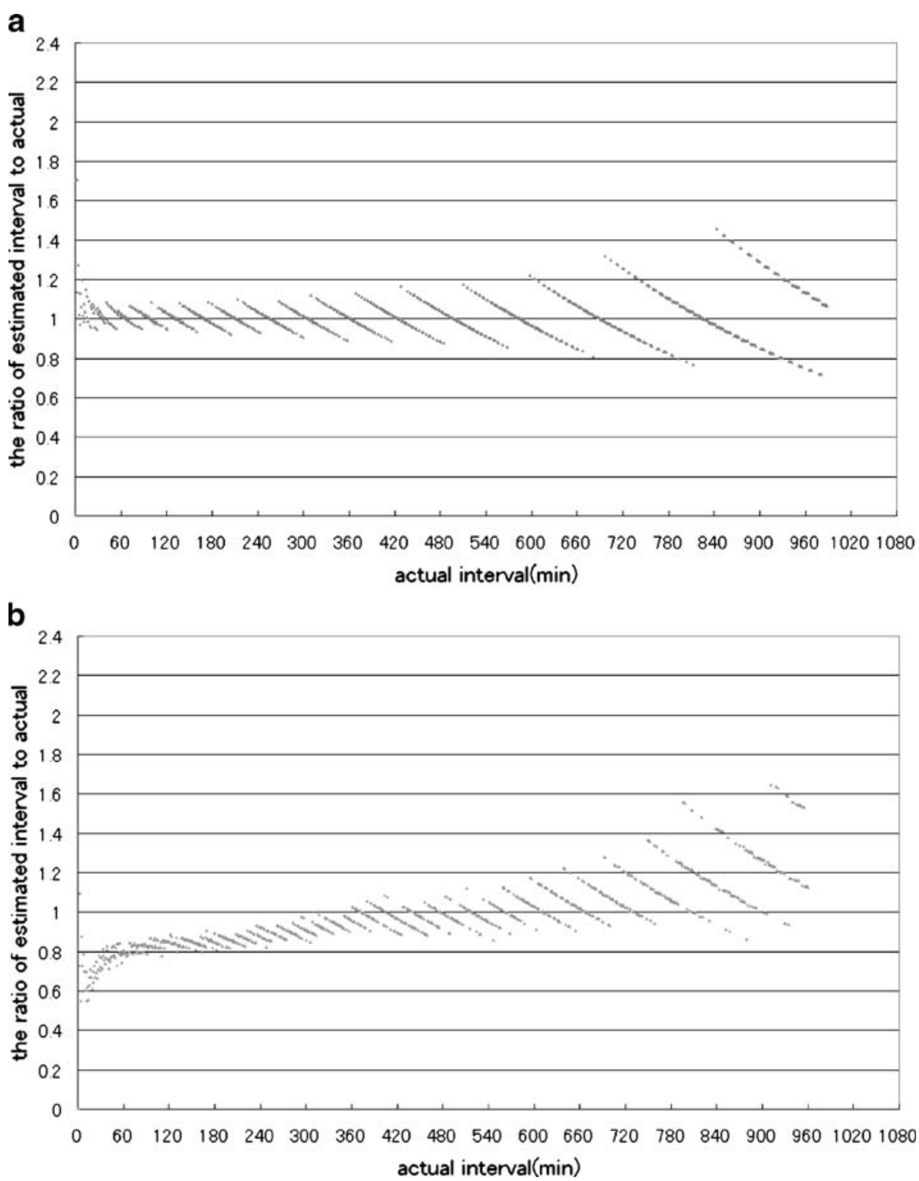
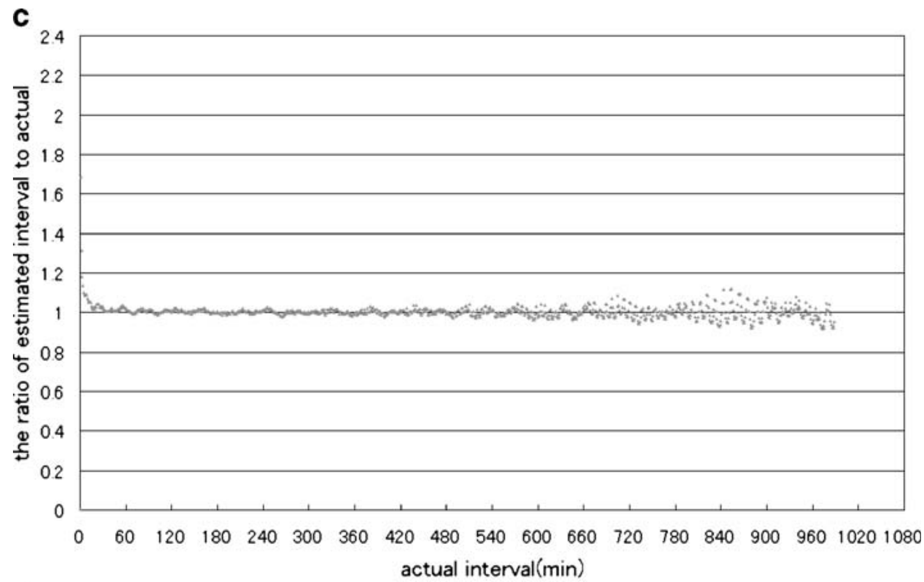
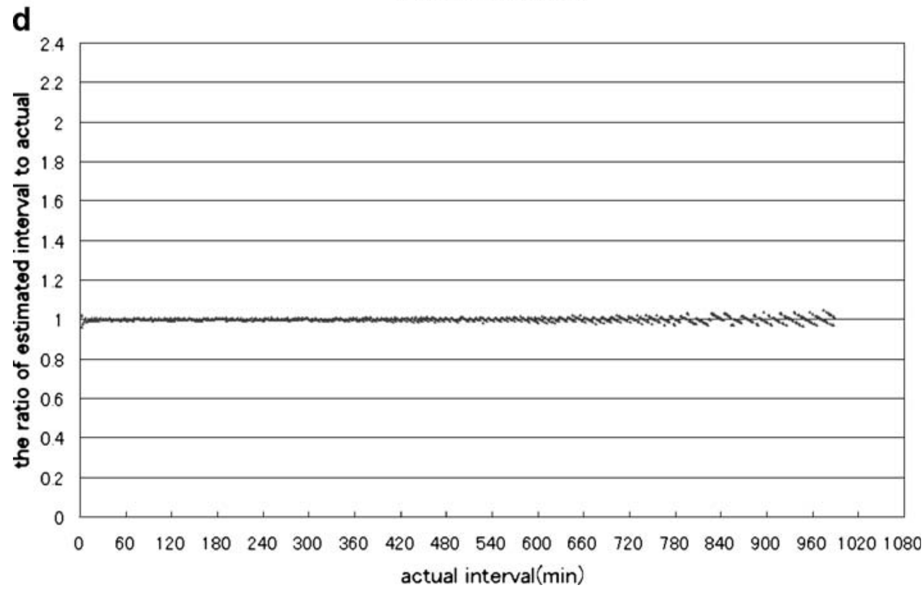


Fig. 2 Ratios of estimated to actual cooling intervals for simulation cases. **a** Two temperatures at intervals of 30 min, **b** two temperatures at intervals of 60 min, **c** 30 temperatures at intervals of 1 min, **d** two temperatures at intervals of 60 min (thermometer resolution is 0.01°C)

Fig. 2 (continued)





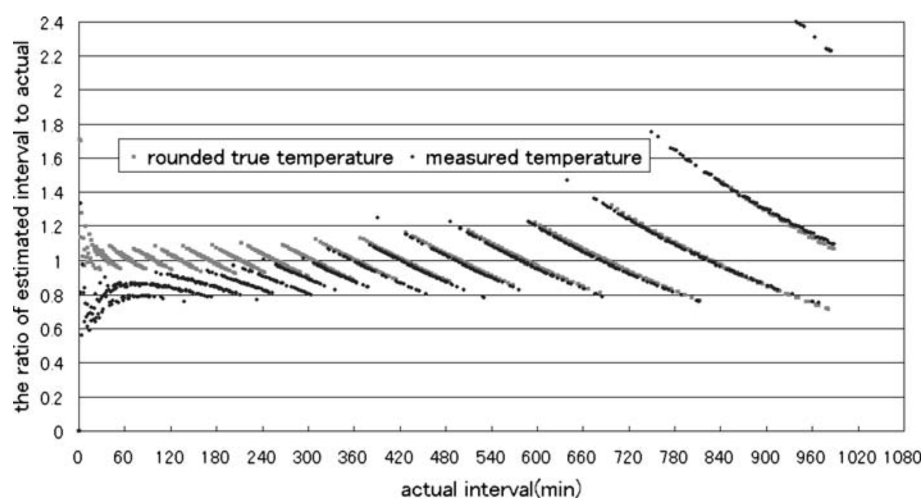


Fig. 3 Superimposition of Figs. 1a (subject case) and 2a (simulation cases)

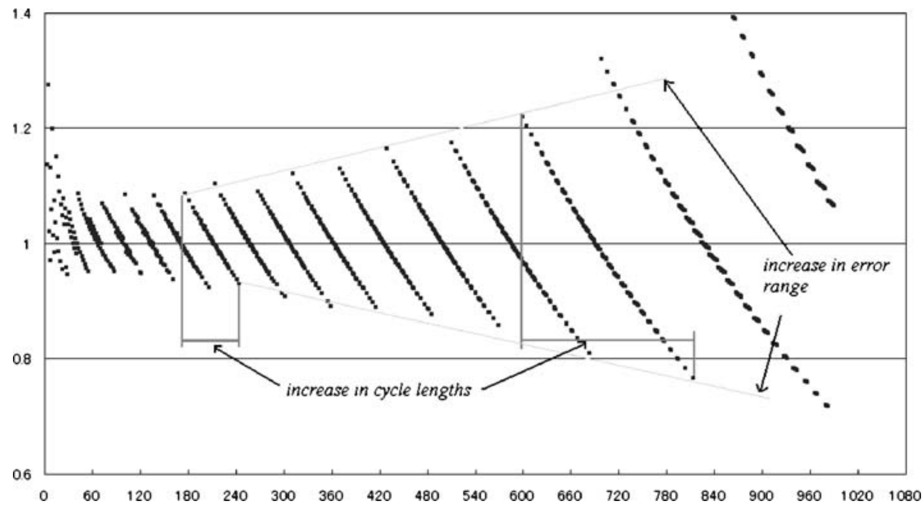


Fig. 4 Characteristics of the error pattern[1]

the refrigerated room at constant temperature could be calculated with less error using any two data points recorded by the datalogger. However, the calculated results varied widely and the estimation errors represented a characteristic pattern: the longer the cooling interval, the greater the error range (amplitude) and the greater the cycle length (Fig. 4).

The estimation errors shown in Fig. 1a might have resulted from measurement and/or calculation errors. Measurement errors are classified into gross mistakes, accidental errors, and systematic errors [14]. In this case, the sensor was fixed in the external canal, and measurements were taken under a constant environment in a refrigerated room. Therefore, it seems unlikely that the characteristic pattern of estimation errors was the result of measurement errors. Calculation errors occur during numerical calculations, and are mainly classified into truncation errors and rounding errors [15]. It seems unlikely that calculation errors were significant because in this case, advanced scientific and engineering computation was not conducted. However, the characteristic pattern seems to suggest an issue with rounding.

The thermometer resolution was 0.1°C; thus, it seems possible that rounding errors occurred not in the calculations but in the thermometer readings; i.e., errors were induced by differences between the thermometer readings and the true temperatures. Therefore, we conducted simulations while considering thermometer resolution in which the true temperatures were rounded off at resolution intervals and from these the cooling intervals were calculated. According to metrology, a "true" value is said to be notional except in a peculiar case and not to be measured practically [16]. In this study, we defined the true value as the temperature explained by Eq. 10 in this simulation. All estimated intervals were plotted and compared with the curve shown in Fig. 1a to determine whether they matched. As shown in Fig. 3, Figs. 1a and 2a overlapped, indicating that the error pattern observed in the measured results (Fig. 2a) agrees closely with the rounded true temperatures (Fig. 2a). Moreover, longer measurement intervals (Fig. 2b), greater numbers of measurements (Fig. 2c), and better thermometer resolution (Fig. 2d), resulted in smaller estimation errors, causing the characteristic error patterns in Fig. 1a to disappear.

From the results of these simulations, we conclude that the cause of the characteristic pattern of the estimation errors was a rounding effect of thermometer resolution. In this case, temperature measurement started at 7 h after death and the postmortem plateau stage was not taken into consideration. There is one report where no plateau was observed when measuring the postmortem fall of the outer ear temperature [17], whereas, there are many reports on the plateau of rectal cooling [12, 18–22]. Rounding errors could occur during this stage; however, the postmortem plateau shows that death has just occurred and that the errors would have less influence in practical cases.

This study shows that the effects of rounding errors caused by thermometer resolution cannot be neglected even under constant environmental conditions. Of course, in practical cases, changes in ambient temperature are unavoidable and probably have a greater impact than the resolution of the thermometer. However, the accuracy of death time estimation will be synthetically influenced not only by the environmental and body conditions but also by measurement conditions, including thermometer resolution. Nokes stated that many recent methods to determine the postmortem period require temperatures to be measured to at least 0.1°C [23]. However, our study indicates that rounding effects at a resolution of 0.1°C are able to influence estimations of the postmortem interval, depend-

[1] The error patterns in Figs. 1a, 2a,b, and d are characterized as the succession of the plot groups shaped "\". The sizes of these groups are expanded. In this article, the distance from the upper-left point to the lower-right point along the transverse axis is defined as the cycle length and along the vertical axis as the error range (amplitude).

ing on measurement conditions and the algorithms of the estimation.

The quantitative results of this study apply only to this case. However, rounding errors can apply to any postmortem cooling process, including rectal temperature. Therefore, such errors should be considered when measuring postmortem temperature. To eliminate such errors, we propose the following:

(a) A thermometer with greater resolution should be used.
(b) The measurement interval should be as long as possible.
(c) As many measurements as possible should be made, and ideally, results should be recorded continuously.

Conclusions

Even under constant environmental conditions it is inevitable that errors will occur during estimations of postmortem intervals. These errors may be the result of thermometer resolution; therefore, a method that minimizes rounding errors should be considered.

References

1. James WRL, Knight B (1965) Errors in estimating the time since death. Med Sci Law 5:111–116
2. Kil'diushov EM (2000) Thermometry of cadavers. Sud Med Ekspert 43:3–5
3. Henssge C (2002) Accuracy of calculated time since death. In: Knight B (ed) The estimation of the time since death in the early postmortem period, 2nd edn. Arnold, London, pp 96–100
4. Henssge C, Beckmann ER, Wischhusen F, Brinkmann B (1984) Determination of the time of death by measurement of central brain temperature. Z Rechtsmed 93:1–22
5. Henssge C (1979) Precision of estimating the time of death by mathematical expression of rectal body cooling. Z Rechtsmed 83:49–67
6. Mall G, Eisenmenger W (2005) Estimation of time since death by heat-flow finite-element model. Part I: method, model, calibration and validation. Leg Med (Tokyo) 7:1–14
7. Mall G, Eisenmenger W (2005) Estimation of time since death by heat-flow finite-element model part II: application to non-standard cooling conditions and preliminary results in practical casework. Leg Med (Tokyo) 7:69–80
8. Mall G, Eckl M, Sinicina I, Peschel O, Hubig M (2005) Temperature-based death time estimation with only partially known environmental conditions. Int J Legal Med 119:185–194
9. Henssge C, Althaus L, Bolt J, Freislederer A, Haffner HT, Henssge CA, Hoppe B, Schneider V (2000) Experiences with a compound method for estimating the time since death. I. Rectal temperature nomogram for time since death. Int J Legal Med 113:303–319
10. Henssge C, Madea B (2004) Estimation of the time since death in the early post-mortem period. Forensic Sci Int 144:167–175
11. Nokes L (2002) Double exponential models. In: Knight B (ed) The estimation of the time since death in the early postmortem period, 2nd edn. Arnold, London, pp 17–18
12. Marshall TK, Hoare FE (1962) Estimating the time of death. The rectal cooling after death and its mathematical expression. J Forensic Sci 7:56–81
13. Bendat JS (1986) Random data analysis and measurement procedures, 2nd edn. Wiley-Interscience, New York, pp 99–106
14. Soumori S, Sato T (2004) Statistics and chemometrics for analytical chemistry, 2nd edn. Kyoritsu, Tokyo, p 4
15. Parker SP (ed) (2003) McGraw-Hill dictionary of scientific and technical terms. McGraw-Hill, New York, p 13
16. Japanese Standard Association (ed) (2002) Quality control-2002. JIS, Tokyo
17. Baccino E, De Saint Martin L, Schuliar Y et al (1996) Outer ear temperature and time of death. Forensic Sci Int 83:133–146
18. Al-Alousi LM (2002) A study of the shape of the post-mortem cooling curve in 117 forensic cases. Forensic Sci Int 125:237–244
19. Hooft P, van de Voorde H (1989) The role of intestinal bacterial heat production in confounding postmortem temperature measurements. Z Rechtsmed 102:331–336
20. Nokes LD, Hicks B, Knight BH (1985) The post-mortem temperature plateau—fact or fiction? Med Sci Law 25:263–264
21. Shapiro HA (1965) The post-mortem temperature plateau. J Forensic Med 12:137–141
22. Hutchins GM (1985) Body temperature is elevated in the early postmortem period. Hum Pathol 16:560–561
23. Nokes L (2002) Temperature measurement. In: Knight B (ed) The estimation of the time since death in the early postmortem period, 2nd edn. Arnold, London pp 23–25