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ORIGINAL ARTICLE

Body mass and corrective factor: impact on temperature-based death time estimation

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Abstract Model-based methods play an important role in temperature-based death time determination. The most prominent method uses Marshall and Hoare's double exponential model with Henssge's parameter determination. The formulae contain body mass as the only non-temperature parameter. Henssge's method is well established since it can be adapted to non-standard cooling situations varying the parameter body mass by multiplying it with the corrective factor. The present study investigates the influence of measurement errors of body mass m as well as of variations of the corrective factor c on the error of the Marshall and Hoare–Henssge death time estimator t_D. A formula for the relative error of t_D as a function of the relative error of m is derived. Simple approximations of order 1 and 0 nevertheless yield acceptable results validated by Monte Carlo simulations. They also provide the rule of thumb according to which the quotient of the standard deviations $D(t_D)$ of the estimated death time and $D(m)$ of the body mass is equal to the quotient of the estimated death time t_D and the body mass m ($D(t_D)/D(m) \approx t_D/m$). Additionally, formulae and their approximations are derived to quantify the influence of Henssge's body mass corrective factor c on death time estimation. In a range of body masses between 50 and 150 kg, the relative variation of the body mass corrective factor is approximately equal to the relative variation of the death time ($\Delta t_D = (t_D/c)\Delta c$). This formula is applied and compared to computations and to experimental cooling data with good results.

Keywords Time since death · Henssge model · Body mass · Measurement errors · Estimation errors · Corrective factor

Introduction

Temperature-based death time estimators are most commonly used for determining death times in the early post-mortem phase. The majority are model-based estimators: They use any form of temperature–time curve $T(t)$ describing the temperature of the cooling body as a function of the time t since death, e.g. [1–7]. The deep rectal temperature has been established since it can easily be measured and only slowly converges to the ambient temperature [8]. The most prominent model is the double exponential model of Marshall and Hoare [3, 9] with the parameter functions by Henssge [4]. To cope with several types of non-standard cooling conditions such as clothing, covering, ground, and convection differing from the experimental standard cooling scenario [4], Henssge devel-

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oped the body mass corrective factor [10]. Multiplying the real body mass m by this factor c leads to a different "virtual" corrected body mass $m' = cm$. The idea is to compensate the difference between the non-standard cooling situation N and the standard cooling situation S by using the model curve $T(m',t)$ of the standard situation S with the modified body mass $m' = c_N m$ to describe the non-standard situation N. Henssge presents non-standard cooling cases N_i in tables with the corresponding corrective factors c_{Ni} [10–12].

Death time estimation by the double exponential model of Marshall/Hoare and Henssge

The double exponential model can be expressed by:

$$(T(t) - T_E)/(T_0 - T_E) = [p/(p - Z)] \exp(-Zt) - [Z/(p - Z)] \exp(-pt) \qquad (1.1)$$

with the rectal temperature T, the environmental temperature T_E, the rectal temperature at death T_0, and the post-mortem time t. From their experiments and physical considerations, Marshall and Hoare [3] decided to use only two parameters in their double exponential model: Based on the equation (Eq. 1.1), they introduced two parameters, p and $Z(S)$, where S represents the so-called size factor of the human body $S=0.8A/m$ with the effective body surface A (unit: square centimeter) involved in heat loss and body mass m (unit: kilogram). Henssge's cooling experiments and physiological as well as physical considerations [4] made him assume proportionality of body surface and body mass. He published a different parameter definition which is adapted here to a more convenient form: $Z=r+sm^{-5/8}$ with $r=-0.0284$, $s=1.2815\ \mathrm{kg}^{5/8}$ and $p = w(T_E)\ Z$ with $w(T_E)=5$ if $T_E \leq 23.3°C$, $w(T_E)=10$ if $T_E>23.3°C$.

The temperature model $T(t)$ of Marshall and Hoare with the parameter definition by Henssge depends on the parameters T_E, T_0, and m.

Algorithm for back-calculating time of death and its error types

Reconstructing the death time t_D, which is more exactly defined as the time between death and rectal temperature measurement, simply means looking for a time since death value t_D which makes the temperature model $T(t)$ assume the measured rectal temperature value T_M if $t = t_D$. The estimated time since death t_D satisfies the following condition:

$$T(T_E, T_0, m, t_D) = T_M \qquad (2.1)$$

The Henssge formula cannot be solved analytically but only numerically or by the well-known nomogram [10] as a combination of numerical and graphical methods. Every numerical method is among other error types subject to errors in the input data, mainly systematic and stochastic errors occurring during measuring temperatures and the body mass or presupposing the rectal initial temperature.

There are several approaches to study the influence of errors in estimating the time since death. Kanawaku et al. [16] studied the effects of rounding errors on post-mortem temperature measurements in the external auditory canal caused by thermometer resolution. Other groups compared real cases with exactly known death times to determine the precision of numerical death time estimation models [1, 4, 10–14, 17–19]. While theoretical analyses run into some mathematical and statistical difficulties, experimental approaches cannot differentiate between the different error types—measurement errors, errors in the model parameters, systematic errors in the model approach—and cannot exclude contingent influences (e.g. errors which emerge from specific circumstances at the experimental site). The present study chooses a theoretical approach combining methods of mathematical analysis and Monte Carlo simulation like in [15]. It deals with the influence of measurement errors Δm of body mass m on the death time estimator's error Δt_D as well as with the influence of the corrective factor c on the death time estimator t_D.

An electronic version of this article containing the formulae derivations in greater mathematical detail is provided as electronic supplementary material (ESM).

Method

Analysing the influence of measurement errors is based on the error propagation law. The algorithm calculating the output data from the input data is a mathematical function with the input data in its range and the output data in its domain. The standard deviation of the output data with respect to the true values can be approximated by a Taylor series expansion of this function. There is no explicit mathematical estimation formula $t_D = F(T_E,T_0,m,T_M)$, so that the Taylor series expansion cannot be computed directly. To overcome this problem, the implicit function theorem and a Monte Carlo simulation are applied [15].

Law of error propagation

Equation 2.1 cannot be solved analytically for t_D necessary for a direct approach to error propagation. The temperature curve $T(t)$ is assumed to be a first order continuously differentiable function defined on the set of real numbers. The mathematical estimation formula F or system function representing the death time calculation algorithm hypothetically computes $t_D = F(T_E, T_0, m, T_M)$. Applying a Taylor series expansion and the implicit function theorem on F yields an analytical expression as a linear approximation for small deviations Δt_D of the estimator $t_D = F(T_E, T_0, m, T_M)$ from the true value $t_D{}^*$ of death time as a function of small deviations Δm of its input parameter body mass m from its true value m^*. Applying the chain rule and some easy transformations provides:

$$\begin{aligned} \Delta t_D/t_D &= \left[(5/8)/\left((r/s)m^{5/8}+1\right)\right]\Delta m/m \\ &=: \mu(m)\Delta m/m \end{aligned} \tag{3.1}$$

The estimator error value Δt_D which can be computed from (Eq. 3.1) adds to the error value from measurement errors of the input parameters T_E, T_0, T_M, and t_M [15]. The factor $\mu(m)$ in (Eq. 3.1) can be linearized in m by a first order Taylor approximation in the neighbourhood of any body mass value m_0. Since our approach concentrates on body masses in the interval (50, 150 kg) the Taylor approximation is computed in the neighbourhood of the mass m_0=100 kg. This leads to the following numerical formula:

$$\mu(m) \approx 1.03151 + 0.00419\mathrm{kg}^{-1}(m - m_0) \tag{3.2}$$

For m=50 kg, the value of μ is approximately 0.82201; for a body mass of 150 kg, the value of μ increases to only 1.24101. Therefore, it is justified to set $\mu(m)$ approximately to the constant value $\mu(m)\approx 1$. Inserting this into Eq. 3.1 leads to the rule of thumb formula:

$$\Delta t_D/t_D \approx \Delta m/m \tag{3.3}$$

Stochastic interpretation of the error propagation law

The error propagation law interprets the variables t_D and m as random variables assuming an additive stochastic model [15]: $t_D{}^*$ and m^* are the constant (correct) values of the variables and added to the stochastic error variables Δt_D and Δm. The input body mass therefore is $m^* + \Delta m$ and the output death time is $t_D{}^* + \Delta t_D$. The probability distributions of the error variables are $P_{\Delta tD}$ and $P_{\Delta m}$ respectively and—consistent with the central limit theorem in probability theory—$P_{\Delta m}$ is assumed to be a Gaussian distribution with expectation value $E(\Delta m)$=0 and variance $V(\Delta m)$. Concerning possible error sources the stochastic parameters $t_D{}^* + \Delta t_D$ and $m^* + \Delta m$, the expected values $E(t_D{}^* + \Delta t_D) = t_D{}^*$, $E(m^* + \Delta m) = m^*$, and the variances $V(t_D{}^* + \Delta t_D) = V(\Delta t_D)$, $V(m^* + \Delta m) = V(\Delta m)$ are of major interest. They can now be approximately calculated using the system function's Taylor series expansion. Since the measurement error in body mass m is stochastically independent from measurement errors in the temperatures T_M, T_E, T_0, and time t_M, covariance matrices have not to be considered.

Monte Carlo simulation

A Monte Carlo simulation is used as independent approach estimating the variance $V(\Delta t_D)$ and verifying equation (Eq. 3.1). A temperature time curve $T(t)$ is computed for all values $t = t_i = i \times h$ (where h=1min) according to the Henssge model (Eq. 1.1) using fixed values of T_E, T_0, and m. A random sample $\{m^1, ..., m^K\}$ of size K from the domain governed by the stochastic Gaussian distribution $P_{\Delta m}$ of body mass values with moments $E(\Delta m)$=0 and $V(\Delta m) = V$ is produced using a PC-based random generator. For every simulated body mass m^k (where k=1,...,K) a death time estimation is performed assuming $T(t,m)$ as correct curve and interpreting $T(t,m^k)$ as temperature measurement resulting in the corresponding death time $t_D{}^k$ defined by the usual condition $T\left(t_D^k, m\right) = T\left(t, m^k\right)$. On the basis of the simulated samples $\left\{t_D^1, \ldots, t_D^K\right\}$ of size K, the standard deviation $D(t_D) = D(\Delta t_D)$ of the difference Δt_D can be estimated using the usual momentum method formula in statistics.

Influence of the corrective factor

The corrective factor c was introduced by Henssge [10] as a means to cope with so-called non-standard cooling conditions. For model parameter calibration, Henssge [4] performed cooling experiments under standardized environmental conditions (body lying on its back on a blanket on top of a metal trolley, no moving air, no irradiation sources). To extend his standard model parameters to conditions that differ from the experimental conditions, he introduced the hypothesis [10] that the temperature–time curve $T(t,m,\mathrm{N})$ of a body of mass m cooling under non-standard conditions N is identical to the temperature–time curve $T(t, m', \mathrm{S})$ of a body of a different mass m'—called the corrected mass—cooling under standard conditions S. This assumption makes the corrected mass m' a function of the original mass m and the non-standard conditions $m' = m'(\mathrm{N},m)$. Henssge partitioned the function m' into two factors: the real body mass m and the corrective factor $c = m'/m$ which depends on the non-standard condition N. But, it turned out that the correction factor c, at least in certain cases, shows an additional dependence [12] on m: $m'(m,\mathrm{N}) = c(\mathrm{N}\ m)m$. Henssge and others presented evidence for those assumptions by cooling experiments using dummies [11] and by real world case studies [11, 14] which provided lists of the form:

Case 1	Body mass m_1	Non-standard cooling condition N_1	Corrective factor c_1
*	*	*	*
*	*	*	*
*	*	*	*
Case K	Body mass m_K	Non-standard cooling condition N_K	Corrective factor c_K

by which he was able to compute the correct death time t_D for each case k by using a specific correction factor c_k given the specific non-standard conditions N_k and the body mass m_k. He proposed to use those lists in future cases with non-standard conditions N and body mass m by choosing a case k with most similar non-standard conditions $\mathrm{N}_k \approx \mathrm{N}$ and similar body mass $m_k \approx m$ from the list and using its corrective factor c_k for death time back-calculation.

By a short calculation, we can see how powerful this method is: Since the corrective factor c transforms the real mass m by multiplication of a factor c into a virtual one, it provides a mass deviation Δm of the sort we considered in Eq. 3.1. Now, it is possible to derive an expression for the deviation Δt_D of the death time estimator t_D which is caused by a deviation Δc of the corrective factor c. Let $m^\#$ be the true body mass and m be the true corrected body mass which yields the true correction factor $c = m/m^\#$ and let m' be the erroneous "corrected" body mass according to a false corrective factor $c' = m'/m^\#$. With $\Delta m = m' - m$, one obtains after some transformations from Eq. 3.1:

$$\Delta t_\mathrm{D}/t_\mathrm{D} = \mu\left(cm^\#\right)\Delta c/c \qquad (4.1)$$

This formula provides control of the death time reconstruction error caused by a numerically fixed uncertainty of the corrective factor. With the approximation μ=1, we come to the following rule of thumb:

$$\Delta t_\mathrm{D}/t_\mathrm{D} \approx \Delta c/c \qquad (4.2)$$

Results

Analytical results (Fig. 1)

The formula (Eq. 3.1) is solved for the proportionality factor μ to display its dependence on the body mass m in the diagram of Fig. 1. The graph of the exact formula (Eq. 3.1) is displayed as a drawn line, whereas the approximation formula (Eq. 3.2) is plotted as a dashed line. The linearized curve matches the exact curve very well with a small maximum deviation of 0.03. This proves the validity of the formula (Eq. 3.2) for computing $\mu(m)$. Henssge's model (Eq. 1.1) is strongly nonlinear concerning the mass m at first sight. It is essential to control the influence of this nonlinearity on the error propagation of m expressed in (Eq. 3.1). The diagram in Fig. 1 presents the factor $\mu(m) = (\Delta t_\mathrm{D}/t_\mathrm{D})/(\Delta m/m)$ on the abscissa and the body mass m on the ordinate. In the body mass interval (50, 150 kg), the factor increases almost linearly from μ=0.84 (m=50 kg) to μ=1.27 (m=150 kg). The narrow range of $\mu(m)$ justifies the previously formulated rule of thumb (Eq. 4.2) approximating $\mu \approx 1$.

Stochastic results (Fig. 2)

The curves presented in Fig. 2 are graphs of the function $D(t_\mathrm{D})$—the standard deviation of the death time estimator t_D as function of the true time of death. The true time between death and temperature measurement is indicated by the ordinate, the standard deviation by the abscissa. The estimation was performed twice, once by the error propagation law (D_EP) and also by Monte Carlo simulation (D_MC) with a sample size of K=1,000. Cooling scenarios with T_E=18°C and T_0=37.2°C under reference standard conditions were computed: (a) with body mass m=50 kg, (b) with body mass m=75 kg, (c) with body mass m=100 kg, and (d) with body mass m=125 kg. The different body masses m were inserted in the Henssge formula for computing D_MC whereas D_EP was computed using formula (Eq. 3.1). Though the parameters T_0 and T_E had to be fixed for the Monte Carlo computations, the results of the Monte Carlo simulations and of the error propagation law were independent of T_0 and T_E. This becomes evident in the formula (Eq. 3.1) which does not contain the variables T_0

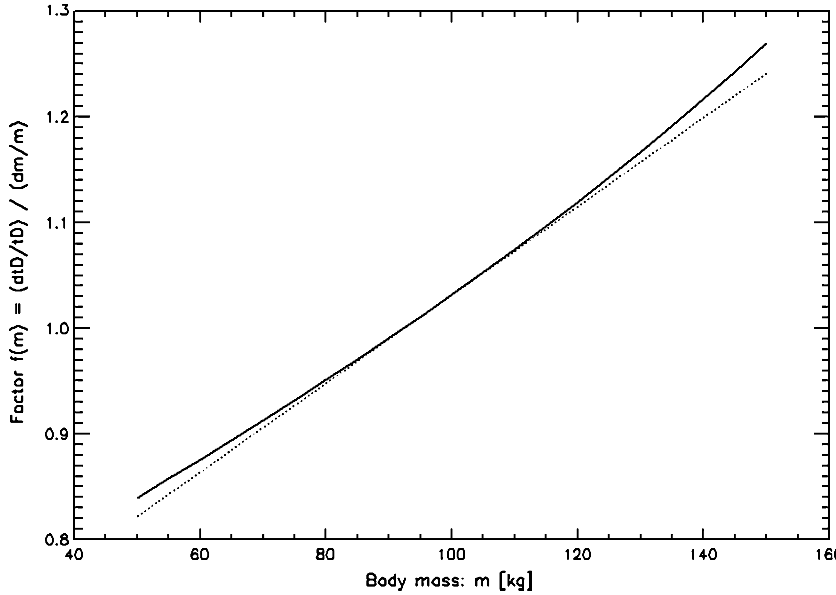

Fig. 1 Factor $\mu(m) = (\Delta t_D/t_D)/(\Delta m/m)$ as a function of m for computation of the influence of errors in body mass and of errors in corrective factor c. *Full line*, $\mu(m)$ exact curve. *Dashed line*, $\mu(m) \approx a + b(m-100\ \mathrm{kg})$ Taylor approximation of order 1 in the neighbourhood of m=100 kg with a=1.03151 and b=0.00419 kg^{-1}

and T_E. The influence of "random noise" in the input variable body mass m on output death time estimate t_D is presented in Fig. 2 for a realistic standard deviation of the body mass measurement of only $D(m)=m/100$. The estimator values D_{EP} and D_{MC} are indicated on the abscissa in relation to the timespan t_D between death and measurement on the ordinate and the body mass m in the different cooling scenarios (a), (b), (c), and d. The graphs of the death time estimator's standard deviations $D_{EP}(t_D)$ computed by the error propagation law (Eq. 3.1) as functions of death time t_D are straight lines. Equation 3.1 shows that the proportionality factor μ establishing the relation between $\Delta t_D/t_D$ and $\Delta m/m$ is constant for fixed m. Solving for Δt_D and inserting $\Delta m = D(m)$ produce a linear equation in t_D. The proportionality constant of this linear relation has the term $(r/s)m^{13/8}+m$ in the denominator, decreasing body masses thus leads to steeper slopes. Accordingly, the line with the steepest slope belongs to cooling scenario (a) with a body mass m=50 kg and the line with most moderate slope to cooling scenario (d) with a body mass m=125 kg. The graphs $D_{MC}(t_D)$ of the Monte Carlo simulations are in good accordance with the graphs $D_{EP}(t_D)$ in all scenarios (a)–(d). This justifies the first order Taylor series approach deriving formula (Eq. 3.1). The standard deviation $D(t_D)$ of the death time estimator t_D following errors in body mass measurement m with a standard deviation $D(m)$= 0.01 m increases from $D(t_D)$=0.01 h at t_D=1 h post-mortem up to $D(t_D)$=0.46 h in case (a), $D(t_D)$=0.415 h in

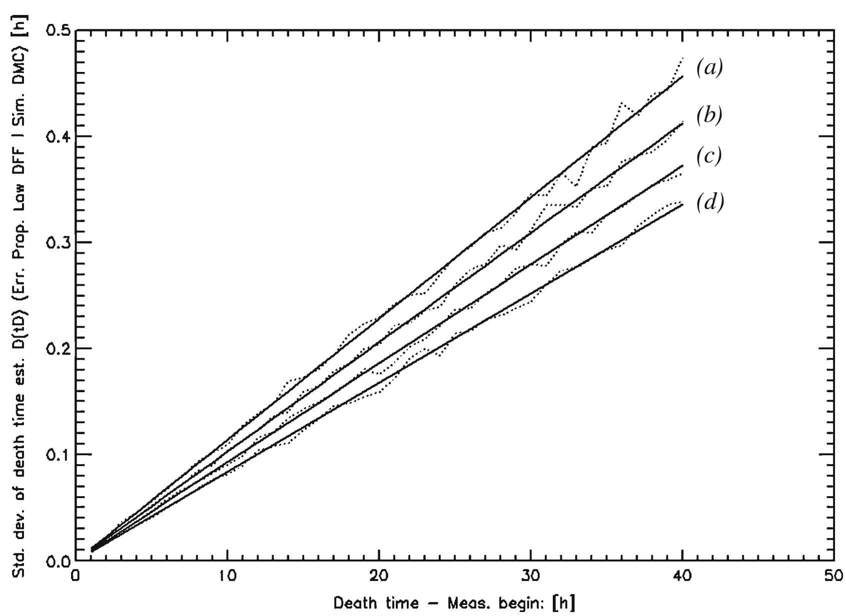

Fig. 2 Standard deviation $D_{EP}(t_D)$ (*solid lines*) and $D_{MC}(t_D)$ (*dotted lines*) of the death time estimator t_D as functions of time between death and measurement for standard deviation $D(m)=m/100$. Computations for fixed body masses m: (**a**) m=50 kg, (**b**) m=75 kg, (**c**) m=100 kg, and (**d**) m=125 kg

case (b), $D(t_D)$=0.375 h in case (c), and $D(t_D)$=0.335 h in case (d) at t_D=40 h. The standard deviation $D(t_D)$ of the death time estimator t_D is in the order of magnitude 1% of the death time t_D estimated given the standard deviation $D(m)=m/100$ of the body mass m measurement. From the diagram in Fig. 2, the following rule of thumb in accordance with Eq. 3.3 can be deduced: The quotient of the standard deviations $D(t_D)$ of the estimated death time and $D(m)$ of the body mass value is approximately equal to the quotient of the estimated death time t_D and the body mass: $D(t_D)/D(m) \approx t_D/m$.

Case results (Fig. 3)

We present the cooling curve of a middle-aged male of 177-cm height and 103-kg weight wearing T-shirt, cotton shirt with long sleeves, underpants, leggings, jeans, socks, and slippers. He collapsed in the cabin of his truck and was unsuccessfully resuscitated in an ambulance, where he died. The environmental temperature at the death scene in the ambulance was T_E=17°C. The deceased was transferred to a climatic chamber 1.48 h after death and the rectal cooling curve $T(t)$ was recorded under strictly controlled environmental parameters (T_E=17°C, no air movement, no radiation, back position on a metal trolley). Several cooling curves $T_{Hi}(t)$ were computed using Henssge's model (Eq. 1.1). Since the body was covered by two to three layers of clothing, corrective factors c ranging from c_0=1.0 to c_3=1.3 were applied [20]. Figure 3 shows the measured cooling curve $T(t)$, the cooling curves $T_{H0}(t)$, $T_{H1}(t)$ $T_{H2}(t)$, and $T_{H3}(t)$ according to the Henssge model with correction factors of c_0=1.0 (H0), c_1=1.1 (H1), c_2=1.2 (H2), and c_3=1.3 (H3) and the environmental temperature $T_E(t)$ in the climatic chamber. The beginnings of the Henssge cooling curves $T_{Hi}(t)$ are adjusted to the true death time. The curve $T_{H0}(t)$ fits the data curve $T(t)$ best. With increasing corrective factor c_i, the temperature curves $T_{Hi}(t)$ stay above the data curve. The deviations can easily be converted graphically into the corresponding errors Δt_D of death time estimation given a fixed point in time t_{D0} and the computed temperature $T_{H0}(t_{D0})$ respectively by shifting the curve $T_{Hi}(t)$ to the left until the time–temperature point (t_{D0}, $T_{H0}(t_{D0})$) meets the curve $T_{Hi}(t)$; the shifted time distance is Δt_{Di}. Taking, e.g. $T_{H0}(t_{D0})$=25°C and t_{D0}=27.1 h, the procedure provides the following t_{Di} values: t_{D0}=27.10 h, t_{D1}=30.00 h, t_{D2}=33.33 h, and t_{D3}=36.52 h. Therefore, we have the following death time estimation errors Δt_{D0}=0 h, $\Delta t_{D1}=t_{D1}-t_{D0}$=2.9 h, $\Delta t_{D2}=t_{D2}-t_{D0}$=6.43 h, $\Delta t_{D3}=t_{D3}-t_{D0}$=9.51 h in reasonable accordance with the rule of thumb error predictions (Eq. 4.2): $\Delta t_{D0}\approx$0 h, $\Delta t_{D1}\approx$2.71 h, $\Delta t_{D2}\approx$5.42 h, $\Delta t_{D3}\approx$8.3 h.

Discussion

The body mass m plays a crucial role in Henssge's model for death time determination [4]. It represents the only non-temperature dependent model parameter, located in the argument of the exponential function and bears the exponent −5/8 (Eq. 1.2) causing a distinct nonlinearity in the cooling model. In real case work, body masses should be measured by gauged scales to avoid systematic errors. Nevertheless, body mass measurement is inevitably subject to measurement noise. Moreover, changes of the body mass

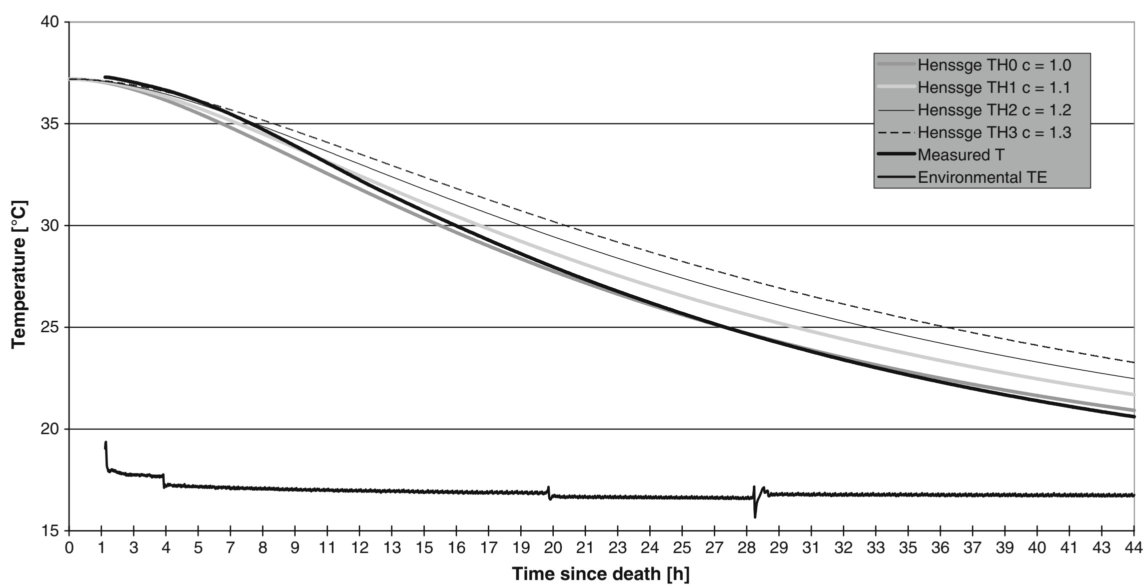

Fig. 3 Climatic chamber cooling experiment. Temperatures: measured $T(t)$; environmental $T_E(t)$; and Henssge with correction factor c_0=1.0: $T_{H0}(t)$; c_1=1.1: $T_{H1}(t)$; c_2=1.2: $T_{H2}(t)$; c_3=1.3: $T_{H3}(t)$

from the death scene to the autopsy when the body mass is measured can occur due to the loss of blood from wounds during transportation of the corpse. The present study investigates first the influence of measurement errors of the body mass m (quantified by the standard deviation $D(m)$) on the standard deviation $D(t_D)$ of the death time estimator t_D and second, the influence of the corrective factor c multiplied to body mass m. Two independent approaches are used for this investigation: first, analytical computation of the error propagation law and second, numerical estimation via Monte Carlo simulation. Identical results from both approaches prove the validity of our results. According to our results, the relative error in body mass (e.g. 1%) corresponds to the relative error in the estimated death time (e.g. 1% as well).

The influence of the body mass errors on death time estimation can be compared to the influence of other input variable errors [15], first, to errors in the presumed initial rectal temperature at death T_0 and second, to errors in the environmental temperature T_E. The error assumptions were adapted to realistic numbers with a standard deviation of the measured body mass $D(m)=0.01$ m, of the initial rectal temperature $D(T_0)=0.5°C$ and of the environmental temperature $D(T_E)=1°C$. Graphically, the T_0-induced standard deviation curve of the death time estimate decreases with time instantly from high values to a low constant socket value. The m-induced standard deviation curve of the death time estimate on the contrary starts from small negligible values and continuously increases with time. Initially during the first hours of cooling, the m-caused standard deviation is small compared to the T_0-caused standard deviation. After 5 h (for smaller body masses) up to 10 h (for high body masses), the m-caused standard deviation reaches the socket value (0.4–0.6 h) of the T_0-caused standard deviation. For death times >10 h, the body mass m-caused standard deviation outweighs the T_0-caused standard deviation since it linearly increases with time. Although there have been several approaches [21, 22] to establish models $T(t)$ which do not necessarily require the environmental temperature T_E, accurate knowledge of this temperature is essential for death time estimation [15]. The T_E-caused standard deviation of the death time estimate exponentially increases with time. Initially, from 0 to 10 h post-mortem, it amounts to less than half of the m-caused standard deviation. From 10 to 25 h post-mortem, the T_E-caused standard deviation reaches to the level of the m-induced standard deviation. In later cooling phases, the m-induced standard deviation becomes negligible compared to the T_E-caused standard deviation.

Apart from measurement errors of body mass, the influence of the corrective factor was investigated. According to our derived rule of thumb, the relative deviation of the corrective factor is approximately equal to the relative deviation of the death time estimate. This rule allows an easy estimation of death times with various corrective factors at the death scene without the necessity of using a computer or the nomogram. The rule also demonstrates the immense power of the corrective factor. An estimated time since death will be doubled by assuming a corrective factor of 2. This strong influence of the corrective factor on the outcome of the death time estimation is contrasted by the uncertainty of choosing the appropriate corrective factor since only relatively few tables with cooling experiments are available to cope with an infinite variety of real death scene boundary conditions.

It is not possible to perform the usual stochastic error analyses for input errors of the corrective factor c according to the law of error propagation since the input random variable c is not defined on a proper probability space with a well-known error probability distribution. Actually, the variable c is defined on the class N × IR of ordered pairs (N,m) with N being any possible non-standard cooling condition and m being any possible body mass, where N is an infinite space without a clear set definition and with no quantifiable mathematical structure or even a topology. Therefore, we only present the above formulae (Eqs. 4.1 and 4.2) to provide a tool for error estimation if the amount of possible error in the variable c is known. Additionally, we present a real cooling case and show the validity of the formula (Eq. 4.2).

Data curves of a cooling experiment in a climatic chamber are presented and compared to Henssge's model cooling curves for different corrective factor values $c=1.0$, $c=1.1$, $c=1.2$, and $c=1.3$. The appropriate corrective factor taking into account the clothing of the body would have been at least $c=1.1$ or $c=1.2$, while the model curve computed with a corrective factor of $c=1.0$ fitted the data curve best. Faint air movement in the climatic chamber necessary to keep the air temperature in the chamber constant is no argument, since the fan is positioned in a considerable height above the trolley with the cooling body and the air movement—measured with a thermoanemometer—produced mean air velocities of only 0.018 m/s, which according to thermodynamics literature [23] can be neglected compared to (the always present) natural convection. In usual routine case work, the real time of death would not have been known and application of higher correction factors would have resulted in an overestimation of the time since death. The results obtained from the graphical comparison of the data curve to the four model curves for the four different corrective factors support the analytical results and the results from the rule of thumb approximation.

References

1. De Saram GSW, Webster G, Kathirgamatamby N (1955) Post-mortem temperature and the time of death. J Crim Law Criminol Police Sci 46:562–577

2. Lundquist F (1956) Physical and chemical methods for the estimation of the time of death. Acta Med Leg Soc (Liege) 9:205–213
3. Marshall TK, Hoare FE (1962) Estimating the time of death. The rectal cooling after death and its mathematical expression. J Forensic Sci 7(1):56–81
4. Henßge C (1979) Die Präzision von Todeszeitschätzungen durch mathematische Beschreibung der rektalen Leichenabkühlung. Z Rechtsmed 83:49–67
5. Henßge C (1988) Death time estimation in case work. I. The rectal temperature time of death nomogram. Forensic Sci Int 38:209–236
6. Hiraiwa K, Ohno Y, Kuroda F, Sebetan IM, Oshida S (1980) Estimation of postmortem interval from rectal temperature by use of computer. Med Sci Law 20(2):115–125
7. Morgan C, Nokes LD, Williams JH, Knight BH (1988) Estimation of the post mortem period by multiple-site temperature measurements and the use of a new algorithm. Forensic Sci Int 39(1):89–95
8. Lim CL, Byrne C, Lee JK (2008) Human thermoregulation and measurement of body temperature in exercise and clinical settings. Ann Acad Med Singapore 37(4):347–353
9. Marshall TK (1969) The use of body temperature in estimating the time of death and its limitations. Med Sci Law 9:178–182
10. Henßge C (1981) Todeszeitschätzungen durch die mathematische Beschreibung der rektalen Leichenabkühlung unter verschiedenen Abkühlungsbedingungen. Z Rechtsmed 87:147–178
11. Henßge C, Madea B (1988) Methoden zur Bestimmung der Todeszeit an Leichen. In: Weinig E, Berg S (eds) Arbeitsmethoden der medizinischen und naturwissenschaftlichen Kriminalistik, Volume 18. Max Schmidt–Römhild, Lübeck. ISBN 3-7950-0624-4
12. Henßge C (1992) Rectal temperature time of death nomogram: dependence of corrective factors on the body weight under stronger thermic insulation conditions. Forensic Sci Int 54:51–56
13. Stipanits E, Henßge C (1981) Präzisionsvergleich von Todeszeitrückrechnungen aus der Rektaltemperatur ohne und mit Berücksichtigung von Einflußfaktoren. Beitr Ger Med 42:323–329
14. Albrecht A, Gerling I, Henßge C et al (1990) Zur Anwendung des Rektaltemperatur-Todeszeit-Nomogramms am Leichenfundort. Z Rechtsmed 103:257–278
15. Hubig M, Muggenthaler H, Mall G (2010) Influence of measurement errors on temperature-based death time determination. Int J Leg Med. doi:10.1007/s00414-010-0453-5
16. Kanawaku Y, Kanetake J, Komiya A, Maruyama S, Funayama M (2007) Effects of rounding errors on postmortem temperature measurements caused by thermometer resolution. Int J Leg Med 121:267–273
17. Henßge C, Althaus L, Bolt J et al (2000) Experiences with a compound method for estimating the time since death. I. Rectal temperature nomogram for time since death. Int J Leg Med 113 (6):303–319
18. Al-Alousi LM, Anderson RA, Worster DM, Land DV (2002) Factors influencing the precision of estimating the postmortem interval using the triple-exponential formulae (TEF). Part II. A study of the effect of body temperature at the moment of death on the postmortem brain, liver and rectal cooling in 117 forensic cases. Forensic Sci Int 125(2–3):231–236
19. Verica P, Janeska B, Gutevska A, Duma A (2007) Post mortem cooling of the body and estimation of time since death. Soud Lék 52(4):50–56
20. Madea B, Brinkmann B (2004) Handbuch gerichtliche Medizin Band 1, 1st edn. Springer, Berlin
21. Green MA, Wright JC (1985) Postmortem interval estimation from body temperature data only. Forensic Sci Int 28(1):35–46
22. Mall G, Eckl M, Sinicina I, Peschel O, Hubig M (2005) Temperature-based death time estimation with only partially known environmental conditions. Int J Leg Med 119(4):185–194
23. Cengel YA (1998) Heat transfer a practical approach. WCG/MCGraw-Hill, New York