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ORIGINAL ARTICLE

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Temperature-based death time estimation with only partially known environmental conditions

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Abstract The temperature-oriented death time determination is based on mathematical model curves of postmortem rectal cooling. All mathematical models require knowledge of the environmental conditions. In medicolegal practice homicide is sometimes not immediately suspected at the death scene but afterwards during external examination of the body. The environmental temperature at the death scene remains unknown or can only be roughly reconstructed. In such cases the question arises whether it is possible to estimate the time since death from rectal temperature data alone recorded over a longer time span. The present study theoretically deduces formulae which are independent of the initial and environmental temperatures and thus proves that the information needed for death time estimation is contained in the rectal temperature data. Since the environmental temperature at the death scene may differ from that during the temperature recording, an additional factor has to be used. This is that the body core is thermally well isolated from the environment and that the rectal temperature decrease after a sudden change of environmental temperature will continue for some time at a rate similar to that before the sudden change. The present study further provides a curve-fitting procedure for such scenarios. The procedure was tested in rectal cooling data of from 35 corpses using the most commonly applied model of Henssge. In all cases the time of death was exactly known. After admission to the medico-legal institute the bodies were kept at a constant environmental temperature for 12–36 h and the rectal temperatures were recorded continuously. The curve-fitting procedure led to valid estimates of the time since death in all experiments despite the unknown environmental conditions before admission to the institute. The estimation bias was investigated statistically. The 95% confidence intervals amounted to ±4 h, which seems reasonable compared to the 95% confidence intervals of the Henssge model with known environmental temperature. The presented method may be of use for determining the time since death even in cases in which the environmental temperature and rectal temperature at the death scene have unintentionally not been recorded.

Keywords Time since death · Postmortem cooling · Temperature model

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Introduction

The temperature-based determination of the time since death commonly requires measurements of the deep rectal temperature and a model of the rectal cooling curve. The deep rectal temperature is preferably used since the measurement site is non-invasively and reproducibly accessible and located near the body core. The model represents a rule for calculating rectal temperatures as a function of time postmortem. The actual death time determination is then performed which is based on the model curve of rectal cooling in a temperature-time diagram starting from a hypothetical time of death *0*. At a real time t a rectal temperature value T is measured. The model curve is shifted along the time axis until it meets the measured rectal temperature. The actual time of death can then be directly read from the starting point of the shifted curve.

There are two basically different approaches to obtain such model curves, which can be described as mathematical and thermodynamic modelling. Most models to be cited from the forensic literature belong to the class of mathematical models [1–5, 9–18, 21–23]. Among them is the most commonly applied model of Henssge [16, 17] which is based on the model of Marshall and Hoare [21–23]. As in all other mathematical models, Henssge's model assumes a known constant environmental temperature throughout the cooling process. There are studies dealing with extending Henssge's model to variable environmental temperature [6], but there are no studies dealing with the application of the model to cases with only partially known environmental conditions. In medico-legal practice homicide is sometimes not suspected immediately at the crime scene but later after admission of the body to a medico-legal institution and a thorough external examination. Valid measurements of the environmental temperature at the crime scene are lacking. In such cases it would be desirable to be able to apply mathematical models to partially unknown environmental temperatures as well.

Methods

Model-based death time determination

The rectal temperature as a function of time t is represented by a model function T, which attributes a rectal temperature $T(t, t_T, T_E, v)$ to each point of time t postmortem. The parameter t_T denotes the death time to be estimated which is the time difference between the time t_R of the rectal temperature measurement and the time t_D of death. The parameter T_E denotes the environmental temperature, which is assumed to be constant. The symbol v summarises all model parameters depending on the cooling body or environmental conditions other than the environmental temperature.

Every reproducible algorithm attributing a good approximation of the death time for an individual body, can serve the death time estimation. The calculation of the estimator is based on the principle that the temperature model curve T should optimally fit the actual temperature-time data $\{ (T_k, t_k) \mid (k = 1, ..., n) \}$ measured in the individual body. The goodness-of-fit can be quantified by the least squares method summing up the squares of the distances between the values of model function and the measurement values:

$$D(t_T) = \sum_k [T(t_k, t_T) - T_k]^2 \tag{1}$$

A necessary condition for the optimum is that the derivative of the distance function $D(t_T)$ for the relative time of death t_T has to be zero with all remaining parameters being constant. This is used to calculate an estimator value t_T* for t_T:

$$t_T^* \leftarrow \sum_k \frac{\partial T(t_k, t_T)}{\partial t} [T(t_k, t_T) - T_k] = 0 \tag{2}$$

Since the model graph does not alter its shape but only gets shifted for the time since death, Eq. 2 becomes:

$$t_T^* \leftarrow \sum_k \frac{\partial T(t_k + t_T)}{\partial t_T} [T(t_k + t_T) - T_k] = 0 \tag{3}$$

Such methods of death time estimation will further be termed shifting procedures. In the most common methods only a single value of the rectal temperature T_1 is recorded at one point of time t_1. Equation 1 is thereby reduced to the solution of a transcendent equation implicitly determining the parameter value:

$$t_T^* \leftarrow T(t_1) = T_1 \tag{4}$$

The temperature model T still depends on the parameter vector v, the environmental temperature T_E and the time since death t_T. This special case will further be termed a single-value procedure.

Initial and boundary values

The physical process of cooling is always described by a solution of the heat transfer equation, which is a partial differential equation of the second order [7]. According to the theory of differential equations the rectal temperature at the time of death will be termed the initial value and the constant environmental temperature the boundary value.

Scalable models

All forensic models describing postmortem cooling belong to a model class which will further be termed scalable models. They are founded on the idea that the quotient of the difference between the rectal temperature T and the environmental temperature T_E and of the difference between the initial temperature T_0 and environmental temperature T_E only depends on the time t postmortem and some further parameters which are not temperatures:

$$\frac{T(t) - T_E}{T_0 - T_E} = f(t, \underline{v}) \tag{5}$$

The dependence on the initial temperature T_0 and on the environmental temperature T_E can be eliminated by selecting a zero position and a scaling factor. This property will further be termed temperature scalability. Solutions of the heat transfer equation also possess this property.

Model-based death time estimation without initial and boundary values

On close inspection of the model Eq. 5 it is in principle possible to estimate the initial temperature T_0 and the environmental temperature T_E from given real rectal temperature-time data. By successive partial derivation for the time t two new equations are obtained from Eq. 5. These three equations together can produce estimators for the time since death t_T, the environmental temperature T_E and for the initial temperature T_0. Eliminating the parameters T_0 and T_E leads to:

$$\frac{\frac{\partial^2 f(t+t_T,\underline{v})}{\partial t^2}}{\frac{\partial f(t+t_T,\underline{v})}{\partial t}} = \frac{\frac{\partial^2 T(t+t_T,\underline{v})}{\partial t^2}}{\frac{\partial T(t+t_T,\underline{v})}{\partial t}} \tag{6}$$

Death time estimation by Eq. 6 may be performed by determining a series of n recorded temperature values T_i and of the first and second order derivatives T'_i und T''_i of the temperature time curve at n points of time t_i from the measured temperature-time data. Then t_T* can be computed using the least squares method:

$$\min \sum_i \left[\frac{\frac{\partial^2 f(t_i+t_T,\underline{v})}{\partial t^2}}{\frac{\partial f(t_i+t_T,\underline{v})}{\partial t}} - \frac{T''_i}{T'_i} \right]^2 \rightarrow t_T^* \tag{7}$$

Equation 7 represents a transcendent and implicit equation for the time since death t_T, which is independent of the initial temperature T_0 and the environmental temperature T_E. Explicit equations for the parameters T_E and T_0 can now be deduced as well:

$$T_E = T(t_T) - \frac{\frac{\partial T(t_i,t_T,\underline{v})}{\partial t} f(t_T,\underline{v})}{\frac{\partial f(t_T,\underline{v})}{\partial t_T}} \tag{8}$$

$$T_0 = f(t_T,\underline{v})^{-1}(T(t_T - T_U) - T_U) \tag{9}$$

Equations 7, 8 and 9 are interesting for theoretical reasons. They prove that the information needed for estimating the time since death is contained in the measured temperature-time data of a cooling corpse. Initial and environmental temperatures are not necessarily required.

The double exponential models of Marshall and Hoare and Henssge

The double exponential model of Marshall and Hoare [21] has the following general form:

$$\frac{T(t) - T_E}{T_0 - T_E} = \frac{p}{p-Z} e^{-Zt} - \frac{Z}{Z-p} e^{-pt} \tag{10}$$

where T is the measured rectal temperature, T_E the environmental temperature, T_0 the initial temperature at death and t is the time since death. According to Henssge [13] the parameters Z and p should be determined as follows:

$$Z = 0.0284h^{-1} - 1.2815\ \mathrm{M}^{-0.625}\ \mathrm{h}^{-1}\ \mathrm{kg}^{0.625} \tag{11}$$

$$p = 5Z \quad \text{falls } T_U \leq 23.2^\circ\mathrm{C} \tag{12}$$

$$p = 10Z \quad \text{falls } T_U > 23.2^\circ\mathrm{C} \tag{13}$$

Application problems of the death time estimator

On close inspection Eq. 7 faces major problems in the practical application. On the one hand the derivatives of first and second order have to be estimated from the temperature-time data. But measured data are noisy (in a signal-theoretic sense) and have an inherent bias. On the other hand difficulties in determining the time since death have to be expected in the initial plateau phase and in the asymptotic final phase of the cooling process when the curves are very flat, since the first order derivative in the denominator becomes zero.

Direct model-based Powell estimation

The direct least squares approximation of model curve and measurement data avoids the problematic estimation of first and second order derivatives:

$$D(t_T) = \sum_k [T(t_k + t_T) - T_k]^2 \tag{14}$$

By minimising this functional the triple of the estimator values can be determined:

$$\min D(t_T, T_U, T_0) \rightarrow (t_T^*, T_E^*, T_0^*) \tag{15}$$

The procedure is applied to the model of Henssge et al. [16]. The favoured method for searching minima of a functional in a three-dimensional space is the algorithm by Davidon, Fletcher and Powell [24], which is numerically very stable.

Experiments

Sample and measurements

Postmortem cooling curves of 35 corpses were recorded. After admission to the medico-legal institute the bodies were stored in a separate room at constant temperature for 12–36 h and the deep rectal temperatures were recorded at intervals of 5 min. Table 1 gives the individual data.

The sudden deaths were most probably of a cardiac or central nervous nature. Since death was witnessed in most

Table 1 Individual data of the cases, identification number, sex, age, body length, body mass, cause of death, month and location of death

No.	Sex	Age (years)	Length (m)	Mass (kg)	t_T (h)	T_E (°C)	Cause of death	Month of death	Location of death
1	m	57	1.75	90	0.6	18.5	Sudden death	June	Outdoors
2	f	64	1.59	82.6	1.5	15.1	Sudden death	January	Indoors
3	f	26	1.80	68.2	5.0	12.3	Suicide	April	Indoors
4	m	75	1.60	85.4	4.1	15.9	Sudden death	May	Outdoors
5	m	43	1.75	67.1	3.1	9.0	Suicide	February	Outdoors
6	f	69	1.53	56.2	4.9	18.3	Sudden death	May	Indoors
7	m	64	1.70	58.4	6.9	8.2	Accident	January	Outdoors
8	m	78	1.85	67.9	3.5	9.9	Suicide	February	Outdoors
9	f	79	1.55	74.3	1.9	9.4	Sudden death	March	Indoors
10	f	21	1.61	66	2.8	14.7	Suicide	June	Outdoors
11	f	40	1.63	62.1	3.7	8.5	Intoxication	October	Indoors
12	m	68	1.69	78.8	1.6	9.1	Sudden death	October	Indoors
13	m	75	1.66	74.1	1.9	7.9	Sudden death	November	Outdoors
14	f	44	1.65	62.6	4.8	6.6	Sudden death	November	Indoors
15	m	68	1.66	52.3	7.0	10.2	Suicide	November	Indoors
16	f	74	1.62	58.8	7.0	11.3	Suicide	December	Indoors
17	m	54	1.82	103.5	1.8	7.9	Sudden death	December	Indoors
18	m	68	1.63	96.6	2.7	12.8	Sudden death	February	Outdoors
19	m	69	1.81	78.4	3.1	7.9	Suicide	February	Outdoors
20	f	86	1.40	36.5	1.7	6.8	Intoxication	March	Indoors
21	m	41	1.89	99.3	4.3	13.6	Sudden death	April	Indoors
22	m	50	1.73	106.4	3.0	12.7	Sudden death	April	Outdoors
23	m	19	1.75	64.3	7.2	10.8	Suicide	May	Outdoors
24	m	68	1.71	62.2	3.0	8.5	Suicide	June	Outdoors
25	m	89	1.66	59.4	2.6	9.2	Suicide	July	Indoors
26	m	37	1.85	145	6.1	10.3	Sudden death	August	Indoors
27	m	60	1.75	95	3.7	22.2	Sudden death	August	Outdoors
28	m	48	1.72	75.5	3.9	9.6	Suicide	August	Indoors
29	m	27	1.74	70	3.8	11.4	Accident	September	Outdoors
30	f	42	1.64	45.8	3.3	9.9	Sudden death	September	Indoors
31	f	85	1.51	48.1	0.9	8.5	Sudden death	September	Indoors
32	m	80	1.66	81.8	4.3	8.6	Sudden death	October	Outdoors
33	f	72	1.67	74.9	4.2	8.1	Sudden death	October	Indoors
34	m	73	1.71	91.1	5.8	8.1	Accident	November	Outdoors
35	f	80	1.63	65.5	2.9	8.5	Sudden death	November	Indoors

t_T Actual time since death. T_E Mean environmental temperature during measurement phase.

cases autopsies were not asked for by the public prosecuters office. Only in the cases 4, 6, 14, 18, 21 and 30 was a postmortem examination carried out. The causes of death were most probably cardiac failure due to hypertrophy (case 4), subarachnoid haemorrhage (cases 6 and 30), myocardial infarction (case 14), myocarditis (case 21). In case 18 the cause of death remained unclear even after the autopsy. The suicides were mostly (cases 5, 8, 10, 19, 23, 24) falls from a height, the remaining were gunshot wound to the head (case 15), hanging (cases 25, 28), heroin intoxication (case 3) and cyanide intoxication (case 16). The accidents were all traffic accidents.

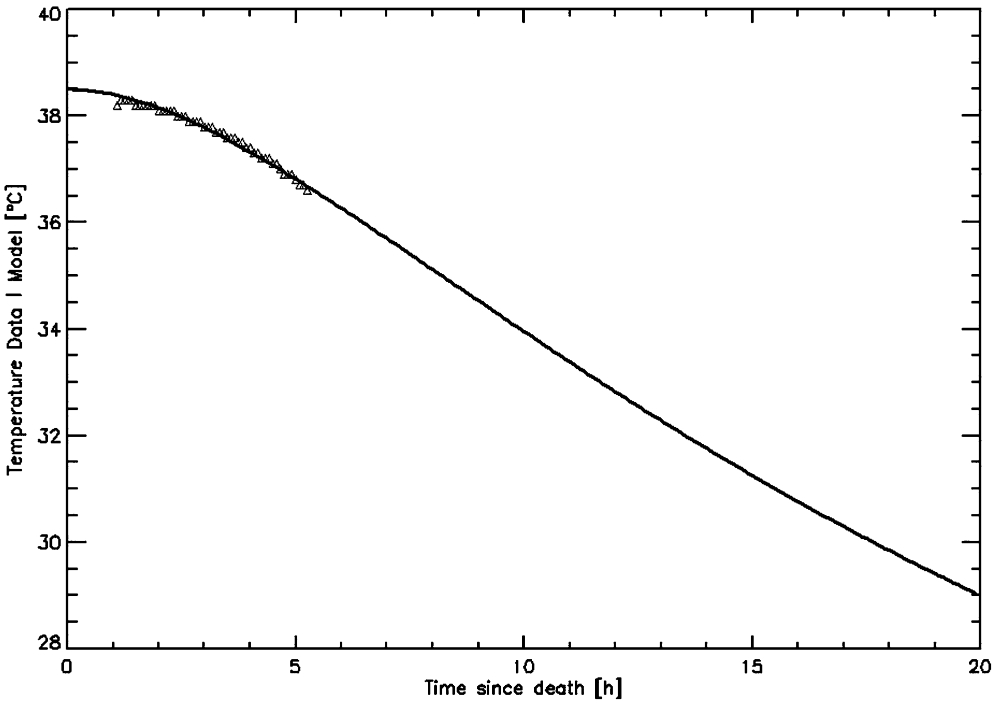
The time of death was known exactly in all cases. The rectal temperatures at the time of death were mostly assumed to be 37.2°C as advised by Henssge and Madea [15]. The ambient temperatures at the time of death before admission to the medico-legal institute were unknown. In most cases they were higher than during the temperature recording. As can be seen from Table 1 most deaths occurred at indoor locations, presumably at room temperature. Some individuals died outdoors but in late spring, summer or early autumn at temperatures partially higher than room temperature. Fewer individuals died outdoors in late autumn or winter at lower temperatures. The environmental temperatures T_E during the measurement period are given in Table 1 as well for comparative reasons.

The problem of the partially unknown environmental temperature

The cooling process of the above experiments is divided into two phases:

1. Phase between death and temperature recording: the environmental temperature in this phase is unknown

Fig. 1 Optimisation procedure in case 1

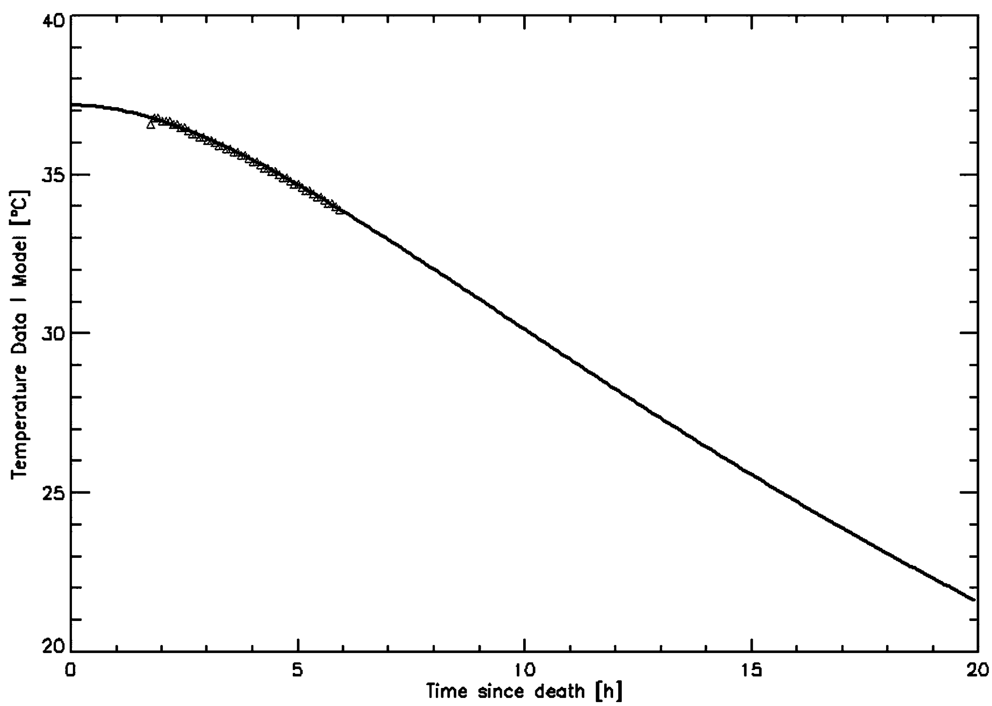


but assumed to be constant. The duration of the phase represents the time since death t_T, which is known but should be reconstructed to test the above estimation method.

2. Phase of temperature recording: the environmental temperature in this phase is known and constant. Rectal and environmental temperatures are recorded every 5 min.

Despite the unknown environmental temperature in the first phase between death and the beginning of the measurements, an estimator t_T* of the time since death t_T should be calculated. The basic idea was that the body core is well insulated from the environment by the body shell. This implies that after a sudden change of environmental temperature the rectal temperature as a core temperature continues to decrease for a certain time span Δt at the same rate as before the sudden change of the

Fig. 2 Optimisation procedure in case 17



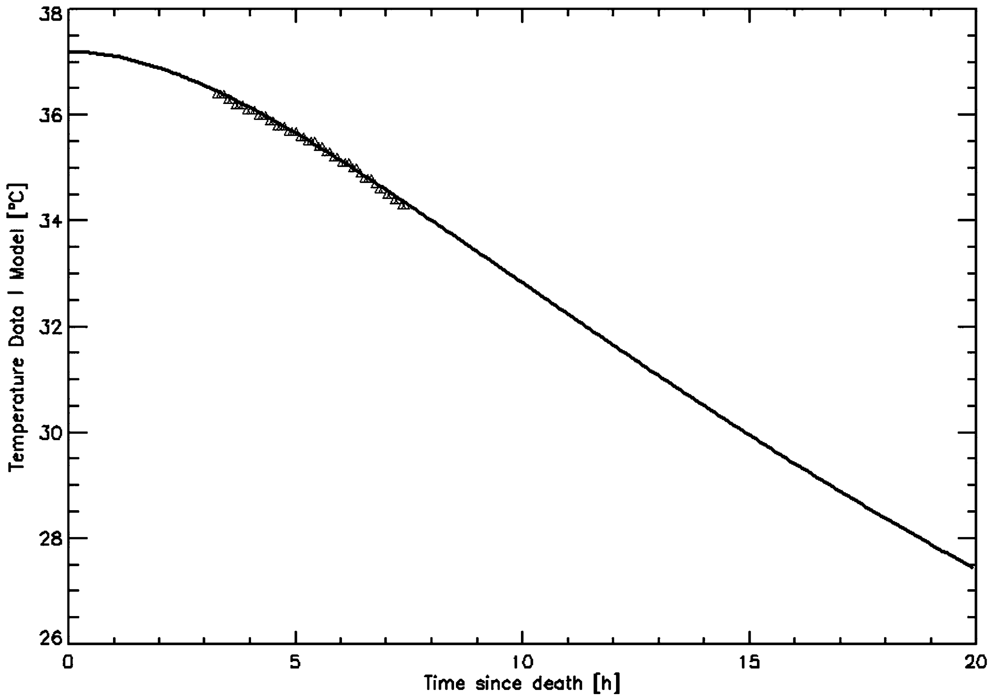


Fig. 3 Optimisation procedure in case 22

environmental temperature. The time span Δt will in future be termed the evaluation window.

In this evaluation window, the time since death and the environmental temperature can be estimated from the recorded rectal temperature values of the second phase by calculating according to Eqs. 14 and 15 as if the environmental temperature was still the same as during the first phase:

$$\min D(t_T, T_E, T_0) \rightarrow \left(t_T^*, T_U^*\right) \tag{16}$$

Results

Optimisation

The results of the optimisation procedures are presented in Figs 1, 2, 3, 4 and 5 by way of example for the cases 1, 17, 22, 7 and 16, respectively. The figures show the optimally fitted model curve (line) and the temperature-time data points (small triangles) within the evaluation window Δt=4.25 h.

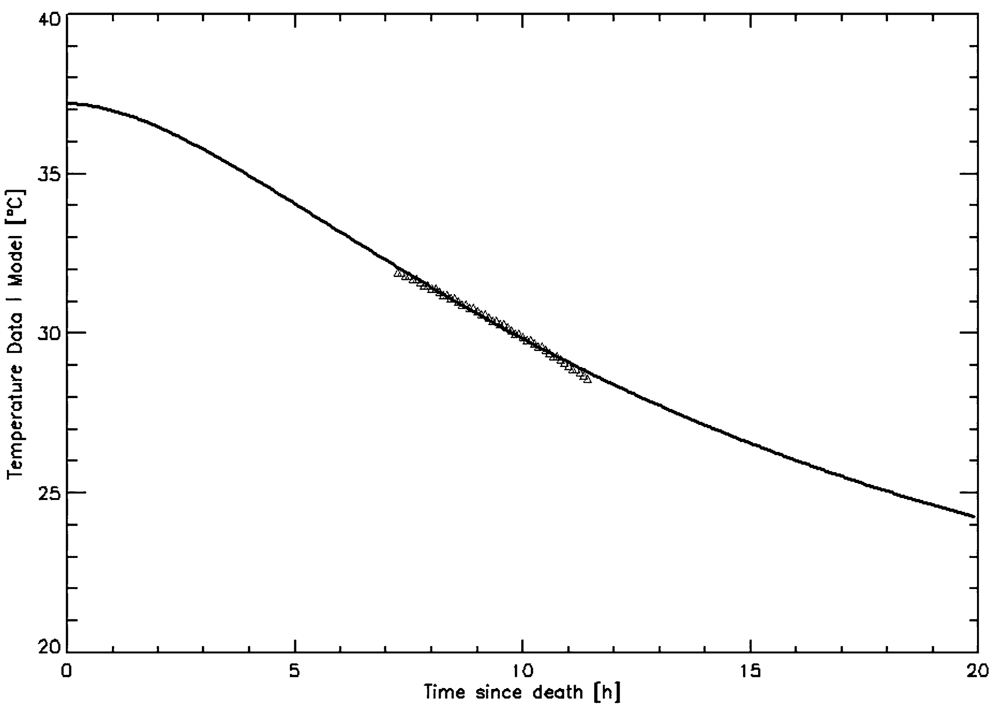


Fig. 4 Optimisation procedure in case 7

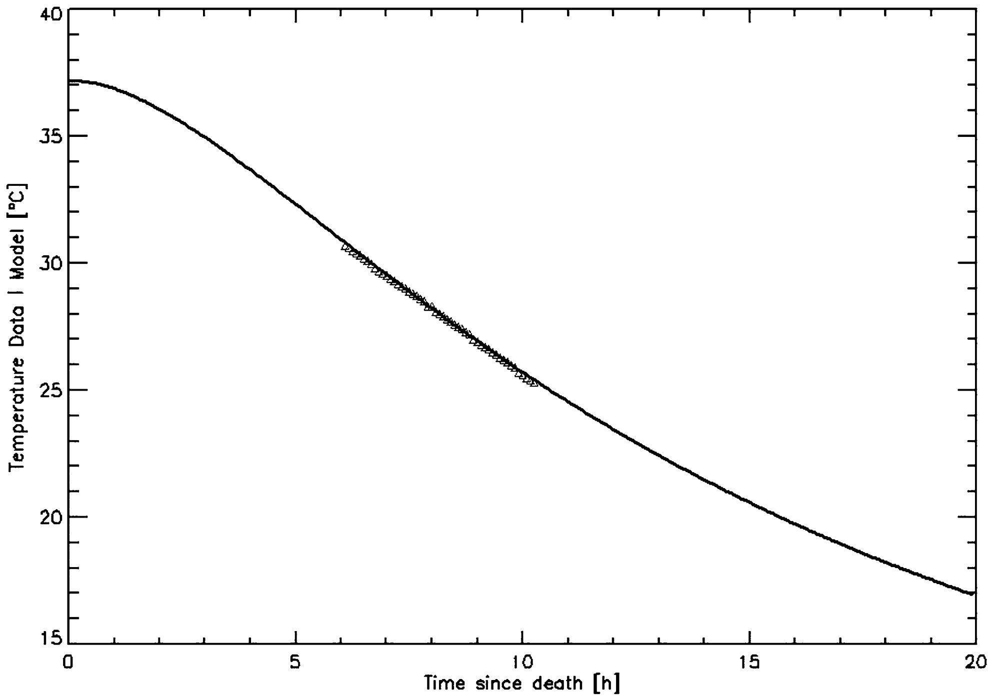


Fig. 5 Optimisation procedure in case 16

Death time estimation

Table 2 summarises the results of the death time estimation. Apart from the case number the first recorded rectal temperature (T_{R1}), the goodness of fit (D), the initial temperature (T_0), the actual time since death (t_T), the estimated time since death (t_T*) and the estimation bias ($b=t_T*-t_T$) are presented. The evaluation window was $\Delta t=4.25$ h. The initial temperature T_0 was assumed to be 37.2°C except for the cases 1, 13, 14, 26 and 31. The rectal temperature data in these cases gave evidence for slight hyperthermia antemortem. Thus the curve-fitting procedure was performed using higher initial temperature values. Initial values of 38°C in cases 13, 14, 26 and 31 and 38.5°C in case 1 provided the best fits. In case 20 the rectal temperature data indicated an initial core temperature slightly lower than 37.2°C. An initial value of 36°C produced the best curve fit in this case.

Bias statistics

The estimation bias was investigated in relation to the time span of the evaluation window in 5 variations:

- $\Delta t_1=0.917$ h corresponding to 11 measurements t_k
- $\Delta t_2=1.750$ h corresponding to 21 measurements t_k
- $\Delta t_3=2.583$ h corresponding to 31 measurements t_k
- $\Delta t_4=3.417$ h corresponding to 41 measurements t_k
- $\Delta t_5=4.250$ h corresponding to 51 measurements t_k.

For each evaluation window Δt_i a histogram H_i of the estimation bias was plotted. The histogram for an evaluation window size of 4.25 h is exemplarily presented in Fig. 6. The bold dashed line gives the number of the experiments with an estimation bias in the time intervals on the x-axis. The thin continuous line connects the centres of the time intervals and thereby interpolates the histogram function.

Figure 7 shows the development of the estimator of the expectation value E(b) and dispersion S(b) of the estimation bias depending on the evaluation window size.

Under the presumption of an approximate Gaussian distribution with an expectation value M and a statistical dispersion S of the bias b, the 95% confidence intervals [b_{95}^{u} , b_{95}^{o}] can be determined (see Table 3).

Discussion

All current mathematical models for temperature-based death time determination [1–5, 9–18, 21–23] presuppose knowledge of the environmental temperature $T_E(t)$ at all times t during the cooling process. Even the method of Green and Wright [11, 12] requires at least the environmental temperature to establish the reference cooling curves. Additionally, the environmental temperature is presumed to be constant throughout cooling. While there are studies dealing with the extension of mathematical models to variable environmental temperatures [6, 19, 20], there is no study dealing with the problem of partially unknown environmental conditions, especially an unknown environmental temperature. But the forensic pathologist is not infrequently faced with cases in which the suspicion of homicide does not immediately emerge at the death scene but much later e.g. at admission and external examination in a medico-legal institution. In such cases the environmental temperatures at the death scene would not have been recorded and therefore remain unknown or can only be roughly reconstructed. A method for applying common

Table 2 Results of the death time estimation

No.	T_{R1} (°C)	D (°C^2)	T_0 (°C)	t_T (h)	t_T* (h)	t_T*−t_T (h)
1	38.2	0.167	38.5	0.6	1.0	0.4
2	37.2	0.185	37.2	1.5	0.7	−0.8
3	32.3	0.461	37.2	5.0	6.2	1.2
4	36.8	0.062	37.2	4.1	2.0	−2.1
5	33.3	0.050	37.2	3.1	4.7	1.6
6	30.0	0.070	37.2	4.9	10.7	5.8
7	31.9	0.358	37.2	6.9	7.2	0.3
8	36.0	0.108	37.2	3.5	2.8	−0.7
9	35.9	0.215	37.2	1.9	3.5	1.6
10	35.9	0.139	37.2	2.8	3.2	0.4
11	34.6	0.988	37.2	3.7	3.5	−0.2
12	36.1	0.426	37.2	1.6	2.3	0.7
13	37.7	0.321	38.0	1.9	0.9	−1.0
14	34.9	0.479	38.0	4.8	3.8	−1.0
15	29.2	0.996	37.2	7.0	6.3	−0.7
16	30.7	0.136	37.2	7.0	6.1	−0.9
17	36.6	0.118	37.2	1.8	1.7	−0.1
18	36.3	0.130	37.2	2.7	2.9	0.2
19	32.3	0.187	37.2	3.1	6.6	3.5
20	35.6	0.337	36.0	1.7	0.3	−1.4
21	36.2	0.223	37.2	4.3	2.8	−1.5
22	36.4	0.076	37.2	3.0	3.2	0.2
23	29.7	0.199	37.2	7.2	8.6	1.4
24	36.5	0.399	37.2	3.0	1.3	−1.7
25	36.1	0.716	37.2	2.6	1.5	−1.1
26	37.6	0.057	38.0	6.1	2.5	−3.6
27	37.1	0.058	37.2	3.7	1.0	−2.7
28	36.5	0.057	37.2	3.9	2.0	−1.9
29	35.2	0.508	37.2	3.8	4.2	0.4
30	34.8	0.930	37.2	3.3	2.8	−0.5
31	37.3	0.665	38.0	0.9	1.3	0.4
32	35.7	0.055	37.2	4.3	4.3	0.0
33	33.7	0.111	37.2	4.2	8.0	3.8
34	32.3	0.095	37.2	5.8	8.8	3.0
35	34.5	0.405	37.2	2.9	5.6	2.7

T_{R1} First rectal temperature data point.
D Goodness-of-fit curve according to Eq. 1.
T_0 Initial temperature.
t_T Actual time since death.
t_T* Estimated time since death.
(t_T*−t_T) Estimation bias.

mathematical models despite partially unknown environmental conditions would be very desirable.

The present study develops a theory for the temperature-based death time estimation with only partially known environmental condition for mathematical models in general (Eqs. 6–9) and provides a practical estimation procedure combining a least squares fit and the Davidon, Fletcher and Powell optimisation [24] (Eqs. 14 and 15). The practical estimation approach is tested for the most commonly applied model of Henssge et al. [16] in data of cooling experiments from 35 corpses with known time of death. The estimation bias is also quantified.

Starting from the general mathematical cooling model (Eq. 5) it is possible to deduce a formula for the death time estimation (Eq. 6) via different transformations including first and second order derivations which does not contain the initial temperature T_0 or the environmental temperature T_E. The formula proves that the information needed for estimating the time since death is in principle supplied by the rectal temperature-time data alone. Practical application of the theoretically deduced formula (Eq. 7) meets with major problems since valid numerical estimations of first and second order derivatives are difficult to obtain. For the practical application a least squares fit using the algorithm by Davidon, Fletcher and Powell [24] as a minimisation procedure was favoured.

The curve-fitting procedure was tested using the model curve of Henssge [13] in rectal cooling data from 35 corpses. The time of death was exactly known in all cases. The environmental temperature at the death scene in the phase before admission to the medico-legal institute was unknown. After admission to the institute the bodies were stored in a separate room at constant environmental temperature and the rectal temperatures were recorded at 5 min intervals for many hours. The aim was to estimate the time of death from the recorded temperature data alone without knowledge of the environmental temperature. The basic idea for the practical application of the method in this case of non-constant ambient temperature was that the body core is thermally well isolated from the environment by the body shell. So after a sudden change of ambient temperature the deep rectal temperature as a core temperature will for a certain period of time—termed the evaluation window—continue to decrease according to the same function of time as before the sudden change of environmental temperature.

The curve-fitting procedure developed led on the whole to valid estimates of the time since death. The radii of the 95% confidence intervals amounted to ±4 h. The size of the interval is relative compared to the 95% confidence intervals of Henssge's method of ±2.8 h with known environmental conditions. A trend of the bias for a positive (over)estimation of the time since death was observed, which could be explained by the experimental situation since the environmental temperature at the death scene in almost all cases was considerably higher than during the rectal temperature recordings.

The Figs. 1, 2 and 3 present cases in which the evaluation window coincided with the plateau (Fig. 1) or with the end of the plateau phase (Figs. 2 and 3). Figures 4 and 5 present cases where the almost linear phase of rectal cooling had begun. The optimisation procedure provided good results in both phases. The phases of the typically sigmoid rectal cooling curves naturally influence death time estimation. The dispersion S(t_T*) increases exponentially in the phase where the rectal temperature asymptotically approaches the environmental temperature. Cooling phases with a low gradient of the rectal temperature curve are generally unfavourable to the estimation of the time since death t_T*. In the initial plateau phase as well as in the final as-

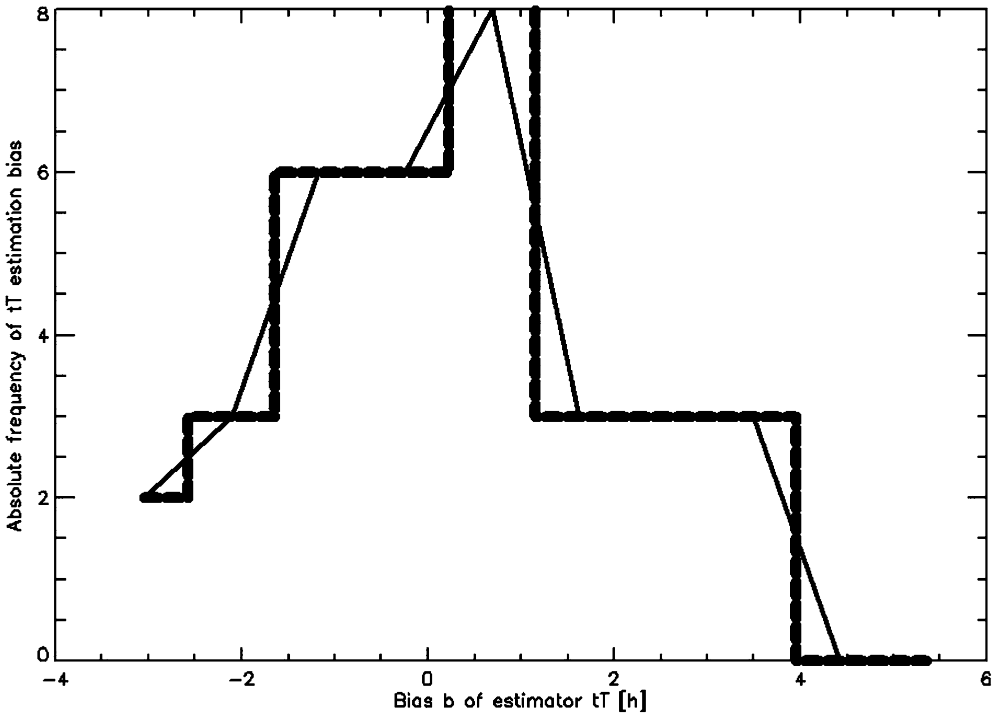


Fig. 6 Histogram of the estimation bias for an evaluation window Δt_1=4.25 h. *Bold line* histogram, *thin line* linearly interpolated histogram function, time intervals 0.5 h

ymptotic phase, higher dispersion values $S(t_T^*)$ have to be expected than in the almost linear phase inbetween.

The size of the evaluation window is of great importance for the goodness-of-fit. A larger window size will lead to an increased effect of the new environmental temperature and therefore to an increased systematic error. A smaller window contains less temperature-time data and will thus lead to an increased dispersion of the death time estimator. Presumably an optimal window size exists. The dispersion in Fig. 7 becomes almost constant for a window size of 4.25 h which therefore seems to be the optimal window size.

In summary, the presented method may be of use for determining the time since death in cases in which the en-

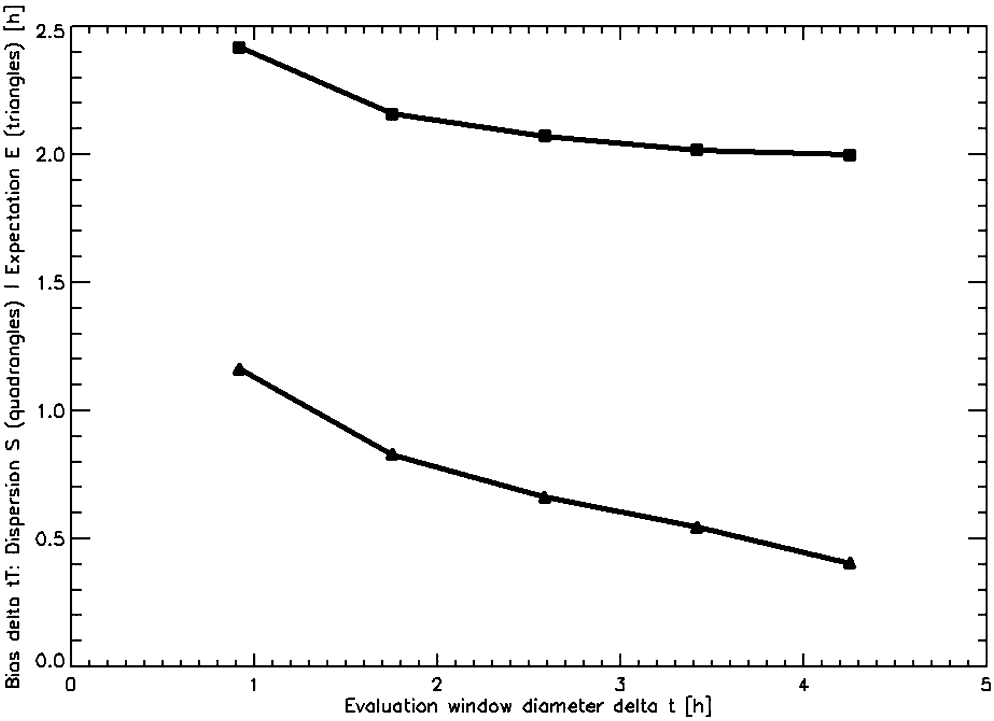


Fig. 7 Estimator of expectation value E(b) (*triangles*) and dispersion S(b) (*squares*) of the estimation bias b as a function of the evaluation window size Δt

Table 3 Evaluation window size Δt_i, expectation value M, dispersion S, and lower b_{95}^{u} and upper b_{95}^{o} limits of the 95% confidence intervals of the estimation bias b

	Δt_i (h)	M (h)	S (h)	b_{95}^{u} (h)	b_{95}^{o} (h)
1	0.917	1.162	2.419	−3.578	5.900
2	1.750	0.828	2.159	−3.392	5.048
3	2.583	0.664	2.072	−3.396	4.720
4	3.417	0.544	2.018	−3.396	4.495
5	4.250	0.405	1.998	−3.505	4.315

vironmental temperature and rectal temperature at the death scene were unintentionally not recorded.

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