Int J Legal Med (2012) 126:79–87
DOI 10.1007/s00414-011-0573-6

ORIGINAL ARTICLE

Database of post-mortem rectal cooling cases under strictly controlled conditions: a useful tool in death time estimation

Holger Muggenthaler · Inga Sinicina · Michael Hubig · Gita Mall

Received: 5 October 2010 / Accepted: 8 April 2011 / Published online: 3 May 2011

Abstract The most common method used in determining the estimated time since death in the early post-mortem phase is back-calculation based on rectal temperature decrease. Cooling experiments are essential for model generation and validation. Post-mortem temperature models are necessary to perform back-calculations. Thus far, cooling experiments have not been performed under controlled environmental conditions. The present study provides data on 84 post-mortem cooling experiments under strictly controlled environmental conditions. For a period of 5 years, starting in 2003, deceased persons with a known time of death and known environmental conditions at the death scene were transferred to a climatic chamber for the process of body cooling. The environmental temperature was programmed to the death scene temperature and kept constant throughout the process of body cooling. Rectal and ambient temperatures were measured every minute. Relevant case-specific information was summarized in a FileMaker database. The database serves as a reference tool for the comparison of real cases in forensic routine and to check the plausibility of model-derived estimates.

Keywords Time since death · Post-mortem cooling · Climatic chamber

Introduction

Knowledge of the time since death is essential in investigating homicide cases, because it represents the alleged time of the offence. The most accurate time-of-death estimates are obtained from the analysis of post-mortem cooling. Generally, the deep rectal temperature is measured, as the measurement location is non-invasive, easily reproducible, and accessible and provides a core temperature.

The estimation of the time since death requires a model curve for the rectal temperature decrease over time which can be obtained using different approaches. Empirical modelling consists of fitting analytical formulae to experimental post-mortem cooling curves [1–4] whereas heat-transfer modelling is based on physical laws [5–7]. Post-mortem cooling experiments are a prerequisite for both approaches but each to a different extent.

Body cooling experiments are difficult to execute. Only the bodies of recently deceased persons with a known time of death could be included in the sample. Animal carcasses cannot substitute for human corpses, since the cooling process strongly depends on the geometry of the body. Additionally, numerous factors such as body constitution, clothing, covering, initial core temperature and ambient temperature influence the cooling rate of a human body.

The first experimental rectal cooling studies date back to the second half of the 19th century [8]. Table 1 shows a concise summary of later experimental approaches from the 20th and 21st centuries.

The problems inherent in performing cooling experiments became evident from the studies cited above. Firstly, there was

---

Electronic supplementary material The online version of this article (doi:10.1007/s00414-011-0573-6) contains supplementary material, which is available to authorized users.

H. Muggenthaler · M. Hubig · G. Mall (✉)
Institute of Legal Medicine, University Hospital Jena,
Fürstengraben 23,
07743 Jena, Germany
e-mail: gita.mall@med.uni-jena.de

I. Sinicina
Institute of Legal Medicine,
Ludwig Maximilians-University Munich,
Munich, Germany

Table 1 Time-of-death determination, experimental studies based on rectal temperature measurements (the initial rectal temperature is the hypothesized temperature at death used in modelling)

Study	Start of measurement	Duration of measurement	Initial rectal temp.	Min./max. ambient temp.	Clothing	Support	Sampling rate	No. of corpses
Mueller, 1937 [17]	10 min–1 1/2 h post-mortem	Max., ≤30 h	Not reported	17−18°C	Unclothed	Not reported	Continuous	25
De Saram et al., 1955 [1]	1–1.5 h post-mortem	Const., 10 h	99.6°F (37.5°C)	74.8°F/88.5°F (23.8°C/31.4°C)	Clothed/sheet	Floor	1/2 h	41
Lyle & Cleveland, 1956 [18]	Not reported	Max., >24 h Avg., 19 h	Not reported	Not reported	Sheet	Wooden pallet, rubber sheet	1/min	56
Fiddes & Patten, 1958 [3]	Not reported	Min., 30 h Max., 70 h	99.0°F (37.2°C)	40–70°F (4.4–21.1°C)	Sheet	Steel trolley wooden-topped	Not reported	>100
Marshall & Hoare, 1962 [4]	Not reported	Min., 12 h Max., 24 h	99.0°F (37.2°C)	40–70°F (4.4–21.1°C)	Unclothed	Steel trolley (in some cases, wooden-topped)	1/2 h	176 (90)
Simonsen et al., 1977 [19]	1/2 h–4 1/2 h post-mortem	Min., 16 h Max., 110 h	Not reported	10–23°C	Clothed	Steel trolley	Not reported	20
Henssge, 1979/1981 [11, 20]	1–6 h post-mortem	Min., 15 h Max., 117 h	37.2°C	9.2–17.4°C	Clothed/unclothed	Steel trolley covered by a sheet	2 min	41
al-Alousi et al., 2001 [21]	15–180 min post-mortem	Min., 2.5 h Max., 60 h	37.0°C	8.83–22.76°C	Unclothed or two sheets	Steel trolley covered by a plastic sheet	Not reported	117

always a delay between the time of death and the start of the experiment. Secondly, the environmental conditions at the time and location of death differed considerably from the environmental conditions during the experiments. Thirdly, all experiments were performed in rooms with environmental temperature fluctuations of several degrees from day to night. According to our own results [9], variations in the ambient temperature considerably decrease the quality of time-of-death estimation. Therefore, only body cooling experiments with a strictly controlled ambient temperature should be used to generate empirical models or to validate heat-transfer models.

The aim of this study was to generate a database with reliable results of post-mortem cooling experiments under strictly controlled conditions. There are three main applications of the database:

1. The provision of valid experimental data on real body cooling cases for the validation and calibration of temperature-based time-of-death estimation models
2. Provision of data to cross-check the results of established estimation methods (non-temperature-based, Henssge,…)
3. The provision of data for back-calculations in similar cases

The emphasis lies on the first two applications as the number of cases in the database is currently too small to match all possible real-world body cooling conditions.

Materials and methods

The data collection was performed in the city of Munich (Germany) from 2003 to 2007. A central 24-h post-mortem examination service was provided by the Institute of Legal Medicine at the University of Munich. After a patient's unsuccessful resuscitation, a forensic specialist was called to the death scene to perform a post-mortem examination. The forensic specialist certified death but postponed the post-mortem examination in appropriate cases, i.e. if there was a known time of death, unclear or suspected unnatural cause of death and the consent of the police. After the forensic specialist had filled out a protocol including the name, time of death, circumstances of death, duration of resuscitation, environmental conditions and in particular, the environmental temperature, he then organized an immediate transport to the mortuary at the Institute of Legal Medicine. Meanwhile, the climatic chamber was programmed to the death scene ambient temperature. Although it was part of the experimental protocol, the rectal temperature was measured at the scene only in a few cases. The reasons are twofold: firstly, a prompt transportation to the institute was of major importance, and secondly, rectal measurements in public proved to be impractical in most cases.

It can be assumed that the ambient temperature at the death scene and during transportation would only have a minor influence on the cooling process since the delay between death and the start of the measurement in the chamber was rather short. Accordingly, arbitrary ambient temperatures could have been programmed in the chamber. However, according to thermodynamics, the maximum influence of the ambient temperature on a body is during the initial post-mortem phase because the temperature gradient between the body and the environment is greatest at this time. Therefore, a change in ambient temperature would have introduced a discrepancy in any back-calculation based on the measured body cooling curves. The short transportation times within the city of Munich with inconstant ambient temperatures therefore had to be accepted for time and effort reasons.

The climatic chamber can generate temperature changes of 0.5°C per minute. Thus, the programmed ambient temperature was easily reached prior to the arrival of the body at the mortuary. Clothing and covering were left untouched, and the body was placed on a steel trolley. Sensors were positioned to measure rectal temperature, various skin temperatures (forehead, chest, abdomen, thigh, calf, upper and lower arm), ambient and trolley surface temperatures and humidity. Data were recorded at a rate of one measurement per minute. The body was transferred to the climatic chamber which was then locked to prevent disturbances. After the measurements had been completed, photographs were taken to document position, clothing and covering. The body was then undressed, and the thickness and material parameters of the clothing were taken. Body weight and height were measured as well as certain constitutional parameters such as the circumferences of upper and lower extremities, chest and abdomen.

A climatic chamber, granted by the German Research Foundation (DFG), was used to control the environmental conditions. The climatic chamber (Feutron® Type 3706/06 RMA 3313) is illustrated in Fig. 1. ALMEMO sensors were used to measure the temperature and humidity. Two ALMEMO data loggers (ALMEMO® 2290–8) with a sampling rate of 1 min^{-1} were used for data acquisition. The temperature in the chamber can be adjusted within the range of −10°C and +50°C with temperature changes of up to 0.5°C per minute. Humidity can be replicated as well. The airflow necessary to maintain a constant ambient temperature in the chamber was applied at a considerable height and distance away from the cooling body and steel trolley. A mean airflow of 0.018 m/s was measured using a thermo-anemometer (ALMEMO FVA 935 TH4) with an accuracy of ±0.04 m/s+1% of the measured value. According to the technical thermodynamics literature [5], this amount of airflow is negligible in comparison to natural convection.

Fig. 1 Climatic chamber

The data were processed and illustrated in Microsoft Excel. A FileMaker© database (version FileMaker Pro 8) was developed for the systematic storage of the data. FileMaker© is a relational database system, where relationships can be established between tables thus enabling a normalized data storage and an effective data search.

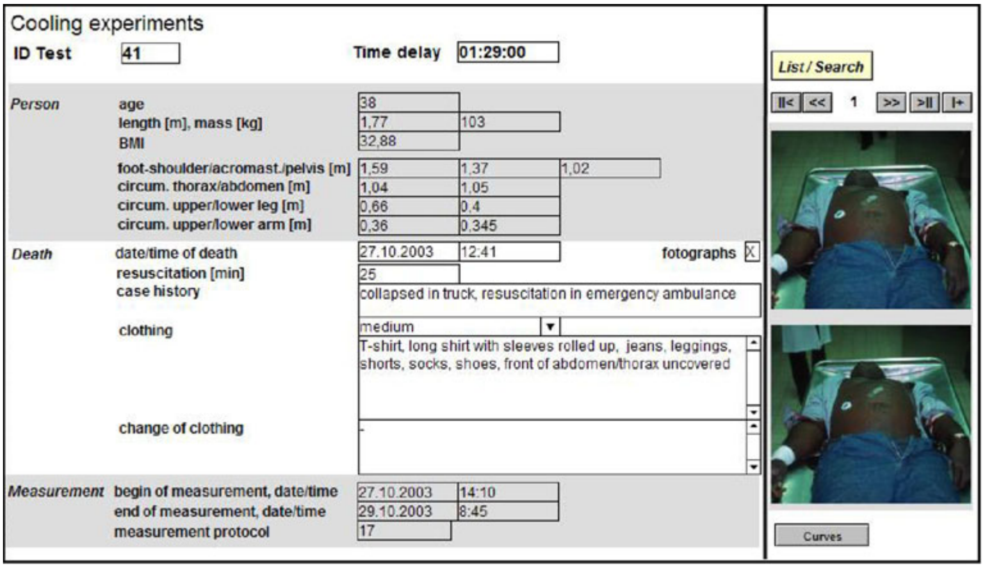
The main objective of the database is to summarize all case-specific information and data to permit a search for different body constitutions, clothing and ambient temperatures. The FileMaker© software enables a search for any combination of field contents without an in-depth knowledge of the database systems.

The database contains all information including the death scene protocol filled out by the forensic specialist (sex, age, time of death, death circumstances and environmental conditions at the death scene), the medico-legal post-mortem examination measurements (body height, body weight, body mass index (BMI), clothing and covering with corresponding layer thicknesses and materials), the photographs and the links to the Excel files containing the measurement data and rectal cooling curves. According to the WHO guidelines (http://www.who.int), the BMI was calculated as follows:

$$BMI = \frac{body\ mass\ in\ kg}{(body\ height\ in\ m)^2}$$

Figure 2 shows the main window of the FileMaker© database. Case-specific information concerning the person, the circumstances of death and the measurements in the climatic chamber are found on the left side of the window. The record navigator and the photographs are located on the right side. The “Curves” button opens the corresponding Excel files with the temperature curves. Furthermore, any search combinations can be entered by using the “List / Search” button. After confirming the search criteria, the database provides the number of found cases and the corresponding records. The study design was approved by the University of Munich ethics committee.

Theoretically, an almost infinite variety of mathematical formulae (exponential, arc tanh, polynomial, Fourier, splines, etc.) could be fitted to match the experimental curves. However, none of those approaches would result in a significant information reduction if the formulae were not



Cooling experiments

ID Test	41	Time delay	01:29:00

Person	age	38		
	length [m], mass [kg]	1,77	103	
	BMI	32,88		
	foot-shoulder/acromast./pelvis [m]	1,59	1,37	1,02
	circum. thorax/abdomen [m]	1,04	1,05	
	circum. upper/lower leg [m]	0,66	0,4	
	circum. upper/lower arm [m]	0,36	0,345	
Death	date/time of death	27.10.2003	12:41	fotographs ☒
	resuscitation [min]	25		
	case history	collapsed in truck, resuscitation in emergency ambulance		
	clothing	medium		
		T-shirt, long shirt with sleeves rolled up, jeans, leggings, shorts, socks, shoes, front of abdomen/thorax uncovered		
	change of clothing	-		
Measurement	begin of measurement, date/time	27.10.2003	14:10	
	end of measurement, date/time	29.10.2003	8:45	
	measurement protocol	17		

Fig. 2 FileMaker database, main window

derived from a real-world physics-based theory. Bearing this in mind, we refrain from generating another mathematical model and concentrate solely on the facts by using the cooling curves directly to cross-check the model-based back-calculations.

Results

Measurements

The sample consisted of 84 bodies of recently deceased persons. Five individuals had already been undressed ante mortem; 17 bodies were undressed immediately post-mortem because the post-mortem examination could not be postponed. In the remaining 62 cases, clothing remained unchanged between the time of death and the start of the experiment.

The experimental cooling curves and a table summarizing case-specific information can be found in the electronic supplementary material (ESM). The table contains ambient temperature, body mass, body length, BMI, initial rectal temperature recording, time delay between the time of death and the start of the experiment, circumstances of death, sex, age, cause or suspected cause of death and whether an autopsy or only an external post-mortem examination was performed.

Table 2 provides basic statistics of the body length, body mass, BMI, first measured temperature T_i, time delay between death and the start of the measurement and the environmental temperature.

The BMI is an index of weight for height used to typecast different body constitutions into six established classes ranging from "underweight" to "obese class III". Figure 3 shows the distribution of the cases in terms of the six BMI classes.

Numerous rectal temperature curves exhibited initial temperatures T_i (first measured rectal temperature in the chamber) which differed considerably from the normal level (37.2°C according to [10]; other authors assumed slightly different values; see Table 1). In 18 of our cases, the first rectal temperature recording exceeded 37.2°C; in 13 cases, the rectal temperature at the beginning of the cooling experiment was below 35°C.

The circumstances of death were documented in all 84 cases. Sixty-two individuals suffered a sudden cardiac arrest. Eighteen individuals committed suicide (by use of a firearm, 2; by hanging, 4; by jumping from a height, 12). Three persons were killed accidentally (falling from a height, 1; accident at work, 2). One person suffered an overdose (heroin). Unfortunately, a medico-legal autopsy was only performed on 28 of the bodies. All cases were investigated by the police, and in the majority of the cases, a natural cause of death, largely due to heart problems, seemed most probable due to medical records and witnesses' observations at the time of death.

Representative examples

Figures 4, 5 and 6 present representative examples at low (2–5°C), medium (15.8–17°C) and high ambient temperatures

Table 2 The statistics of parameters that influence body cooling rates

	Mean	Minimum	Maximum
Body length (m)	1.73	1.44	1.95
Body mass (kg)	81.9	43.8	158.9
BMI (kg/m^2)	27.3	16.9	52.8
T_i (°C)	36.2	31.1	38.7
Time delay (min)	129.3	70.0	210.0
T_E (°C)	14.5	−4.3	29.8

BMI body mass index, T_i: first rectal temperature measured, *time delay* time between death and start of measurement, T_E environmental temperature

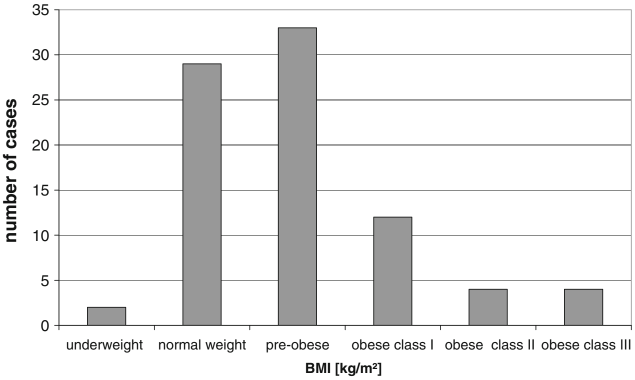


Fig. 3 Histogram with the number of cases in each BMI class

(19.4–21°C). The corresponding case conditions such as ambient temperature, constitution and clothing can be taken from Table 3.

Discussion

Experimental measurements

All body cooling experiments were previously conducted by other study groups at “room” temperatures. With the exception of De Saram's study, which was conducted in a tropical environment, cooling experiments under extreme ambient temperatures are lacking. The “room” temperature experiments from the other studies are furthermore all biased by seasonal and day-to-night temperature fluctuations of several degrees. Error analyses [9] of the Henssge model proved a considerable influence of errors in the ambient temperature on death time estimation.

A climatic chamber was used to store the cooling bodies during the experiment for the first time in this study. We were thus able to accurately simulate the seasonally different environmental temperatures at the death scenes. Day-to-night fluctuations of several degrees encountered in all other experiments were thereby avoided. Furthermore, disturbances by airflow or temperature exchange, present also in Henssge's experiments, were prevented by locking the climatic chamber throughout the experiment. Our study also provides body cooling curves in a wide range of ambient temperatures ranging from −4°C to +29°C for the first time. Additionally, our study design allowed us to prevent long-term ambient temperature shifts during our experiments. The only ambient temperature shift that could not be circumvented was during the transport of the body from the death scene to the mortuary. Nevertheless, transportation times could be kept shorter than 30 min since only cases within the city of Munich were included, and the undertaker was informed of the necessity of a quick transport to the Institute of Legal Medicine's mortuary situated in the city centre. All other experimental studies had to deal with severe bias caused by ambient temperature

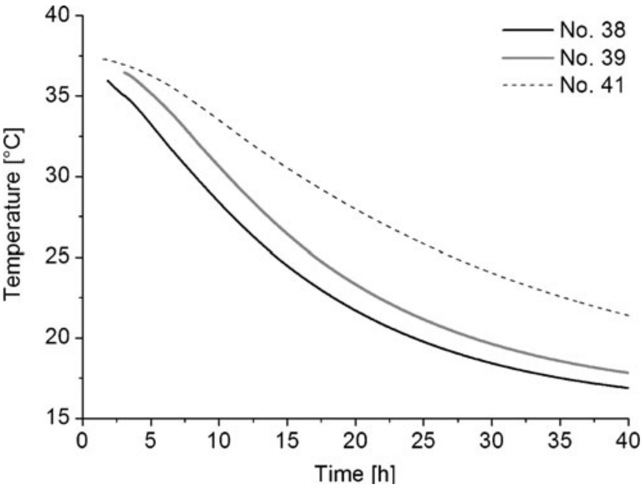


Fig. 5 Example cases, mid ambient temperatures (nos. 38, 39 and 41)

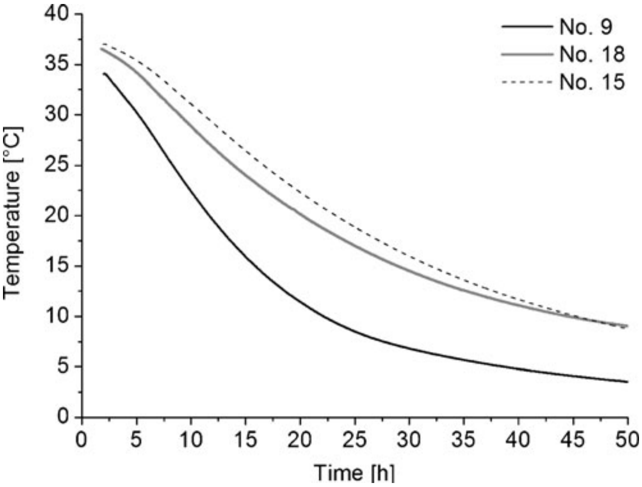


Fig. 4 Example cases, low ambient temperatures (nos. 9, 18 and 15)

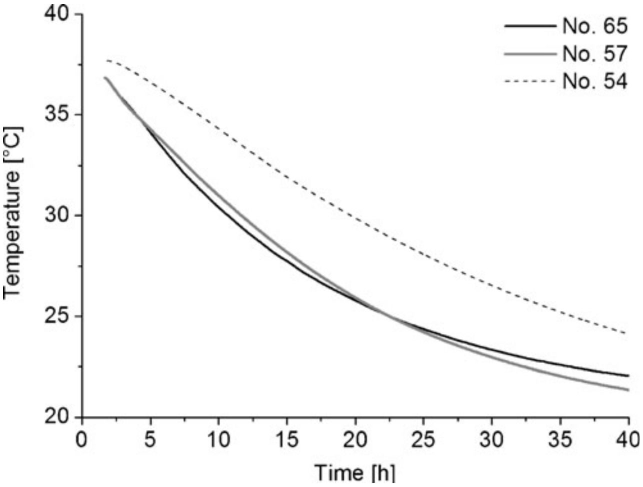


Fig. 6 Example cases, high ambient temperatures (nos. 65, 57 and 54)

Table 3 Case-specific data of representative example cases

No.	T_E (°C)	m (kg)	L (m)	BMI (kg/m^2)	Delay (min)	T_i (°C)	Circumstances of death	Sex	Age (years)	Autopsy/external examination	Cause of death	Clothing
9	2.0	59.3	1.73	19.5	119	34.0	Suicide/jump from height	M	33	Autopsy	Polytrauma	Briefs, left shoe, socks
15	3.5	79.8	1.53	34.1	115	37.0	Cardiac arrest	F	81	Examination	No tentative diagnosis	Coat, pullover, undershirt, tights, panties , lined boots, bra
18	5.0	79.2	1.73	26.5	105	36.5	Cardiac arrest	M	71	Autopsy	Congestive heart failure	T-shirt, long-sleeved shirt, knee-length shorts, trousers, socks, shoes, front of abdomen uncovered
38	15.8	63.1	1.74	20.8	110	35.9	Suicide/jump from height	M	55	Examination	Suspected polytrauma	Jeans, T-shirt, briefs, socks, shoes, sweatshirt, abdomen nearly uncovered
39	16.2	77.9	1.77	24.9	173	36.2	Cardiac arrest	M	65	Autopsy	Pulmonary embolism	Unclothed
41	17.0	103.0	1.77	32.9	89	37.3	Cardiac arrest	M	38	Autopsy	Myocardial infarction	T-shirt, long-sleeved shirt with sleeves rolled up, jeans, leggings, briefs, socks, shoes, front of abdomen/thorax uncovered
54	19.4	158.4	1.78	50.0	110	37.7	cardiac arrest	M	53	Examination	No tentative diagnosis	Briefs, undershirt, shirt, jeans, shoes, abdomen/thorax uncovered
57	20.0	68.4	1.69	24.0	100	36.8	Cardiac arrest	F	69	Autopsy	Pulmonary embolism	T-shirt, slip, long trousers, stockings, abdomen uncovered
65	21.0	58.5	1.76	18.9	170	35.9	Suicide/gunshot	M	21	Examination	Brain injury	Undershirt, long-sleeved shirt, open jacket

T_E ambient temperature, *m* body mass, *L* body length, *delay* time between death and start of measurement, *BMI* body mass index, T_i first measured rectal temperature

shifts between the time of death, the transportation to the mortuary and the experiment. Furthermore, most authors undressed the corpses after admission to the mortuary, leading to additional bias. To avoid this additional bias, we left clothing and covering untouched as at the time of death or after the attempted resuscitation whenever possible.

Henssge [11] assumed an average physiological body core temperature of 37.2°C. Fluctuations between 36.7°C and 37.7°C over the course of the day were previously described [10]. As in most of the cases, the first rectal temperature was taken in the chamber; mild hyper- or hypothermia at the time of death could not be ruled out. This immanent anomaly associated with the experimental study design could not be avoided for ethical reasons. In 18 of our cases, the first rectal temperature recording exceeded 37.2°C, although 90 to 210 min had passed since the time of death. Even in the case of a distinct temperature plateau, we assume that after a mean delay of 2 h, a body core temperature of 37.2°C or higher indicates hyperthermia at the time of death. The first measured temperature T_i in the 18 cases proved that the body core temperature at the time of death must have been higher than 37.2°C. Human thermoregulation is a complex process, which maintains equilibrium between heat loss and heat production in order to keep the body core temperature constant within a narrow physiological range. Hyperthermia can result from pathological processes or from an overproduction of heat, e.g. during physical exercise. Lim et al. [12] measured an increase of the gastrointestinal temperature from 37.6°C before exercise to 39.3°C during a 45-min period of exercise with a peak value of 40.3°C. In our case sample, one person (no. 47; T_i, 38.7°C; delay, 109 min) collapsed while playing football, and another man collapsed during strenuous physical work (no. 33; T_i, 37.6°C; delay, 130 min). In two other cases (nos. 63 and 75), the individuals were bowling or cycling, respectively. In the remaining 14 cases with elevated initial core temperatures in our sample, pathological processes have to be discussed. Unfortunately, an autopsy was only performed in three cases with the following results: two myocardial infarctions and one polytrauma after a suicidal fall from a height. In the 11 remaining hyperthermia cases, infectious diseases might have contributed to an elevated body core temperature. However, the persons in question died suddenly in public places; hence, a pronounced symptomatic fever, which would have prevented them from leaving their home, does not seem to be plausible in these cases. A different type of fever known as psychogenic fever, which lacks physiological or pathological causes, is discussed in the literature as well [13]. This might have played a role in the suicide cases.

In 13 cases, the rectal temperature at the beginning of the cooling experiment was below 35°C. In eight cases, the ambient temperature was below 5°C so that an accelerated cooling of the body has to be considered. In one case, a 33-year-old woman died from a narcotic overdose (heroin) which could have induced hypothermia. Shields and Sixsmith [14] report 17 cases of patients, who survived severe hypothermia with body core temperatures between 23.8°C and 31.6°C. The majority were chronic alcoholics or narcotic addicts.

All cases with an elevated or reduced initial temperature show that the assumption of an initial body core temperature of 37°C or 37.2°C does not necessarily reflect real conditions. This is confirmed by Demierre et al. [15] in a retrospective study with 744 cases demonstrating that "hyperthermia is a finding with an incidence of 10% of all cases of violent death". They also give a systematic review of potential hyperthermia risk factors. According to our own error analyses [9], errors in the initial temperature measurement can lead to considerable errors in the time-of-death estimation only in the very early cooling phase.

Our sample is a typical subset of all sudden death cases which occur in public places. Therefore, only a minority of the cases were autopsied and/or underwent a histological examination. This fact might be a point of major criticism since the possible causes of hypo- and hyperthermia may remain unresolved. However, there seems to be a crude disparity between expenditure and benefit concerning autopsy and histology. Firstly, neither an autopsy nor a histological examination guarantees a clarification of the non-normothermic body core temperatures, and secondly, relatives would have to approve such procedures. Additionally, the autopsy and histology of each case would have required substantial costs and manpower which were not at the disposal of the scientists performing this study. Moreover, none of the earlier studies dealing with the subject realized a high autopsy rate.

Database

The most established temperature-based time-of-death estimation method according to Marshall and Hoare with Henssge's parameter definitions uses the body mass but not body length. Yet, thermodynamic theory indicates that the constitution plays a role in body cooling. Thus, the BMI was included in the database providing another filter criterion.

The application of the database in forensic case work is demonstrated by the following real-world scenario. At 6 p.m., a 60-year-old male was found dead in his apartment lying in ventral position on a carpeted floor. At 10 p.m., the deep rectal temperature was 27°C, and the room temperature was 25°C, which was kept constant by central heating. The man was clothed with a shirt, undershirt, trousers, underpants and socks. The trousers and underpants were pulled down below the buttocks. Body height was measured at 1.78 m and body weight at 83.3 kg (BMI, 26.3 kg/m^2; overweight). The corrective factor was set to 1.0 in order to take the pulled-down trousers into account.

The criteria for filtering the database are:

- Surrounding temperature, >22°C and <27°C
- BMI between 20 and 30 kg/m^2
- Naked or sparsely clothed

As a result, the database provides the following two cases with almost comparable conditions:

- Case no. 80: m=85.9 kg, h=1.80 m, T_E=24.5°C, regularly fitting trousers
- Case no. 81: m=73.7 kg, h=1.80 m, T_E=24.8°C, regularly fitting trousers

For both cases, the Henssge model was applied using the appropriate corrective factor of 1.1. The experimental temperature curves and the temperature curves calculated with the Henssge model are presented in Fig. 7.

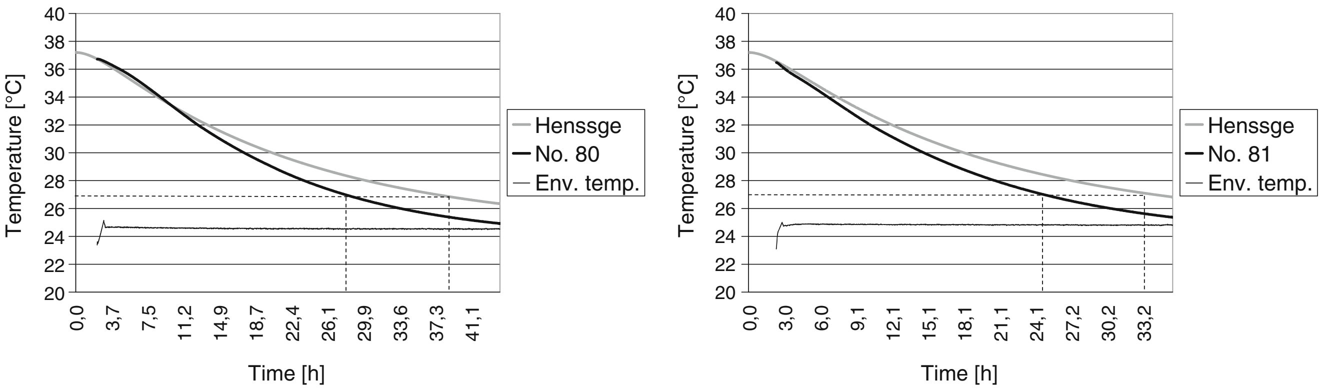


Fig. 7 Experimental (*black*) and Henssge curves (*grey*) for case nos. 80 (*left*) and 81 (*right*)

In case no. 80, a rectal temperature of 27°C was reached at about 27 h post-mortem; in case no. 81, it was reached after approximately 24 h post-mortem. As the diagrams show, the Henssge model curve produces post-mortem intervals that exceed the experimental intervals by more than 10 h. Subtraction of 10 h from the intervals (Q=0.17)—as recommended by Henssge [16]—would therefore provide (minimum) post-mortem intervals that are in accordance with the database-derived estimations. The perpetrators later confessed to having entered the apartment at approximately 8:30 p.m. the day before (real post-mortem interval, 25.5 h). Thus, the database provided realistic time-of-death estimates.

Representative cases

Figures 4, 5 and 6 demonstrate experimental cooling curves for low, medium and high ambient temperatures. The curves in each of the figures appear to be completely different, although they were measured at almost equal ambient temperatures. Indeed, these differences can be explained by different boundary conditions, especially in terms of clothing and body mass index. Within the low ambient temperature range, the fastest decline in body core temperature was measured in case no. 9 with a BMI of 19.5, an ambient temperature of 2°C and the individual sparsely clothed. In the other two cases (nos. 18 and 15), the body mass indices of the clothed bodies were 26.5 and 34.1, respectively. The medium and high ambient temperature range examples show considerably slower cooling rates for case nos. 41 and 54, which is consistent with the corresponding body mass indices (32.9 and 50.0).

The question arises whether confidence intervals can be computed for this application since the database offers the possibility to establish a back-calculation for cases that are admissibly similar to the cases recorded in the database. However, it does not seem to be feasible to calculate valid confidence intervals at this time with the number of n=84 cases currently stored in the database. To understand the why, it is helpful to look at Henssge's confidence interval estimation method. He recorded several hundred time–temperature pairs for each cooling case and performed a back-calculation using his parameterized model for each of the temperatures. The deviation of the back-calculated value from the time value was recorded in a histogram, from which his confidence interval was easily derived. As our method does not use a model, a similar approach is not possible. Instead, a measured curve could play the role of Henssge's model curve while another measured curve from an admissibly similar case would act as the measured data. This approach postulates the classification of the n cases in many subgroups, where the cases in every subgroup are admissibly similar to all other cases within the same subgroup. The parameters for this classification must at least be the body mass and the cooling conditions covered in the Henssge model by the correction factor cf. A hypothetical classification in terms of body mass m and corrective factor cf, dividing each of the axes m and cf into 10 intervals, results in a number of k=100 cells. For n=84 cases, this stratification, though giving only a very raw division on the mass scale, does not make statistical sense.

Conclusions for practice

The experimental rectal temperature curves are accessible for the scientific community in the ESM. The selection of comparable database cases should be based on following basic criteria:

- Ambient temperature
- Body stature in terms of BMI (body mass and height)
- Clothing

In general, the database cases cannot account for all boundary conditions found in forensic practice. The interpretation of the experimental cooling curves depends on the database cases, especially in terms of matching boundary conditions. If there are database cases with similar conditions (e. g. T_E±1°C, BMI within the same BMI class, thin/medium/thick clothing), model-based time-of-death estimations can be compared directly to the experimental data. If the database lacks cases with similar conditions, cases can then be chosen with non-matching boundary conditions. In this way, obviously shorter or longer time-of-death estimates could be produced (e.g. similar ambient temperature but considerably lower or higher BMI values) to be used as upper and lower boundaries of the time-of-death interval.

Acknowledgements This work was supported by grant MA 2501/1–2 from the DFG (Deutsche Forschungsgemeinschaft).

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. Fiddes FS, Patten PT (1958) A percentage method for representing the fall in body temperature after death. J Forensic Med 5(1):2–15
4. 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
5. Cengel AY (1998) Heat transfer: a practical approach, Internationalth edn. McGraw-Hill, New York
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):1–14
7. Hiraiwa K, Ohno Y, Kuroda F, Sebetan IM, Oshida S (1980) Estimation of post-mortem interval from rectal temperature by use of computer. Med Sci Law 20(2):115–125

8. Rainy H (1869) On the cooling of dead bodies as indicating the length of time that has elapsed since death. Glasg Med J 1:323–330
9. 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
10. Henssge C, Madea B (1988) Methoden zur Bestimmung der Todeszeit an Leichen. Schmidt-Röhmhild, Lübeck
11. Henssge C (1979) Die Präzision von Todeszeitschätzungen durch mathematische Beschreibung der rektalen Leichenabkühlung. Z Rechtsmed 83:49–67
12. 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
13. Oka T, Oka K, Hori T (2001) Mechanisms and mediators of psychological stress-induced rise in core temperature. Psychosom Med 63(3):476–486
14. Shields CP, Sixsmith DM (1990) Treatment of moderate-to-severe hypothermia in an urban setting. Ann Emerg Med 19(10):1093–1097
15. Demierre N, Wyler D, Zollinger U, Bolliger S, Plattner T (2009) Elevated body core temperature in medico-legal investigation of violent death. Am J Forensic Med Pathol 30(2):155–158
16. 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 Leg Med 113 (6):303–319
17. Mueller B (1937) Mastdarmtemperatur der Leiche und Todeszeit. Dtsch Z gesamte gerichtl Med 28:172–177
18. Lyle HP, Cleveland FP (1956) Determination of the time of death by body heat loss. J Forensic Sci 1:11–24
19. Simonsen J, Voigt J, Jeppesen N (1977) Determination of the time of death by continuous post-mortem temperature measurements. Med Sci Law 17(2):112–122
20. Henssge C (1981) Todeszeitschätzungen durch die mathematische Beschreibung der rektalen Leichenabkühlung unter verschiedenen Abkühlungsbedingungen. Z Rechtsmed 87:147–178
21. al-Alousi LM, Anderson RA, Worster DM, Land DV (2001) Multiple-probe thermography for estimating the post-mortem interval: I. continuous monitoring and data analysis of brain, liver, rectal and environmental temperatures in 117 forensic cases. J Forensic Sci 46(2):317–322