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Technical note: Excel spreadsheet calculation of the Henssge equation as an aid to estimating postmortem interval

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ABSTRACT

In forensic cases for which the time of death is unknown, several methods are used to estimate the postmortem interval. The quotient (Q) defined as the difference between the rectal and ambient temperature ($Tr - Ta$) divided by the initial difference ($T0 - Ta$) represents the progress of postmortem cooling: $Q = (Tr - Ta)/(T0 - Ta)$, ($1 \geq Q \geq 0$). Henssge was able to show that with the body weight and its empirical corrective factor, Q can be reasonably *predicted* as a double exponential decay function of time (*Qp(t)*). On the other hand, actual Q is *determined* as *Qd* by measuring *Tr* and *Ta* under an assumption of $T0 = 37.2$ °C. Then, the *t* value at which *Qp(t)* is equal to *Qd* ($Qd = Qp(t)$) would be a good estimate of the postmortem interval (the Henssge equation). Since the equation cannot be solved analytically, it has been solved using a pair of nomograms devised by Henssge. With greater access to computers and spreadsheet software, computational methods based on the input of actual parameters of the case can be more easily utilized. In this technical note, we describe two types of Excel spreadsheets to solve the equation numerically. In one type, a fairly accurate solution was obtained by iteration using an add-in program Solver. In the other type (forward calculation), a series of *Qp(t)* was generated at a time interval of 0.05 h and the *t* value at which *Qp(t)* was nearest to *Qd* was selected as an approximate solution using a built-in function, XLOOKUP. Alternatively, a series of absolute values of the difference between *Qd* and *Qp(t)* ($|Dq(t)| = |Qd - Qp(t)|$) was generated with time interval 0.1 h and the *t* value that produces the minimum $|Dq(t)|$ was selected. These Excel spreadsheets are available as Supplementary Files.

1. Introduction

Newton's Law of cooling states that the rate at which the temperature of an object cools is proportional to the difference in temperature *between the object and its surroundings*. If someone leaves coffee at 70 °C at a room temperature of 20 °C, the temperature of the coffee will decrease to 60 °C and then 50 °C over time. In everyday life, this phenomenon would be interpreted as an increase in the temperature decrease of 0 °C (=70 − 70) to a decrease of 10 °C (=70 − 60) and then to a decrease of 20 °C (=70 − 50), and ultimately leading to a final temperature of 50 °C (=70 − 20). However, from Newton's perspective, this temperature decrease is grasped as *a decrease* of the difference in temperature between the coffee and the room from 50 °C (=70 − 20) to 40 °C (=60 − 20) and 30 °C (=50 − 20) and ultimately to a difference of 0 °C (=20 − 20).

When estimating time since death, various observations can be considered. Among these, rectal temperature (*Tr*), which except for in very hot environments such as tropical areas and intense heat in summer of temperate areas, decreases toward ambient temperature (*Ta*) and can be used to extrapolate time since death by various calculation methods.

Henssge postulated that under the assumption of *Tr* at death being

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37.2 °C, $Q = \frac{Tr - Ta}{37.2 - Ta}$ (*Q* being a quotient) would decrease in a predictable manner. This was expressed as a mathematical function of the postmortem interval (*t*): *Qp*(t). Thus, the time at which *Qp*(*t*) was equal to the actual quotient determined by measurements (*Qd*) could be used as a good estimate of the postmortem interval.[1] However, the equation ($Qd = Qp(t)$) (the Henssge equation) could not be solved analytically due to the inclusion of two exponential decay terms. Henssge therefore developed a graphical method for solving this equation using a set of two nomograms, one for lower and another for higher ambient temperature (Henssge's nomogram method).[2–6]

While the nomogram method to estimate time since death remains in use,[7–15] computational methods are increasingly used today, including in the form of a trustworthy website managed by Schweitzer that returns an approximate numerical solution[16,17] and commercial software released by Henssge.[18] This technical note describes another option for making these computations using Microsoft Excel (Excel 365, Microsoft Japan, Tokyo, Japan; US headquarters: Microsoft Corporation, Redmond, WA, USA). Two types of spreadsheets were prepared, and the solution strategy of the first type was iteration, which was performed using an iterative program, Solver Add-in (Frontline Systems, Inc., Incline Village, NV, USA). The solution strategy of the second type was forward calculation, and two algorithms were adopted. In one algorithm, a series of *Qp(t)* was generated for all possible times and the *t* value at which *Qp(t)* was the nearest to *Qd* was selected as an approximate solution using a built-in function, XLOOKUP. The other was an algorithm originally devised for the website,[17] wherein a series of the absolute values of the difference between *Qd* and *Qp(t)* ($|Dq(t)| = |Qd - Qp(t)|$) was generated and the *t* value that produced a minimum $|Dq(t)|$ was selected.

2. Formulas constituting Henssge equation

The Henssge equation is complex and involves five variables: rectal temperature (*Tr*), ambient temperature (*Ta*), body weight (*W*), an empirical corrective factor (*CF*), and PMI(*t*). These variables are related to each other by several formulas.

Assuming that *Tr* at death is 37.2 °C and *Ta* remains constant from the time of death to the time of measurement, the quotient representing the fraction of remaining possible heat loss (*Qd*) is determined by[3]

$$Qd = \frac{Tr - Ta}{37.2 - Ta} \tag{1}$$

such that *Qd* is a dimensionless number between 1 and 0.

Based on the pioneering work by Marshall and Hoare,[19–21] Henssge[3,8,18] derived a formula for the quotient that predicts a standardized temperature (*Qp*) as a function of time (*Qp*(*t*)):

$$Qp(t) = A \times \exp(B \times t) + (1 - A) \times \exp\left(\frac{A}{A-1} \times B \times t\right), \tag{2}$$

where *A* and *B* are constants given by[1–5,9,18]

$$A = 5/4 \text{ for } Ta \leq 23^{\circ}C;\ A = 10/9 \text{ for } Ta > 23^{\circ}C \tag{3}$$

and

$$B = -1.2815 \times (CF \times W)(-5/8)\hat{+}0.0284. \tag{4}$$

With increasing *t*, *Qp*(*t*) monotonically decreases from 1 to 0, matching the range of *Qd*. The first exponential term is a principal term that represents cooling according to Newton's Law of Cooling, and the second term is a corrective term introduced to express the postmortem temperature plateau. Values of *A* and the related coefficients ($A = 5/4$, $1 - A = -1/4$ and $A/(A-1) = 5$ for $Ta \leq 23$ °C, and $A = 10/9$, $1 - A = -1/9$ and $A/(A-1) = 10$ for $Ta > 23$ °C) are the result of Henssge's insights that there is a relationship between the rate for Newton's Law of Cooling and the duration of the postmortem temperature plateau.[1,2,22]

In formula 4, the environmental conditions for the decedent are considered in the term $CF \times W$, as an adjustment of the actual weight of the body. The default value of $CF = 1$ represents the standard condition of a naked body lying extended on its back on a thermally neutral base in still air in a closed room with no strong source of heat radiation. On the other hand, $CF < 1$ indicates the condition of accelerated cooling of the body, which can practically be expressed as decreased body weight. In contrast, $CF > 1$ indicates the condition of decelerated cooling, which has the same effect as increased body weight. For example, *CF* for a 70 kg body (actual weight) wearing thick clothing such that cooling is slowed would be 1.4, resulting in a *Qp* equivalent to that for a naked, 98 kg body ($70 \times 1.4 = 98$). *CF* values for various non-standard cooling conditions were provided by Henssge and others,[4,5,9,13,16,18] and an appropriate choice of *CF* is key to reaching a reasonably realistic estimation.

The Henssge equation linking these quotients is[3,8,18]

$$Qd = Qp(t) \tag{5}$$

and it is solved numerically to find *t* that satisfies this equation for a given set of inputs (*Tr*, *Ta*, *W*, *CF*). To use an add-in iterative program, Solver, the equation was rewritten as

$$Dq = Qd - Qp(t) \tag{6}$$

so that Solver numerically finds *t* such that *Dq* becomes close to 0.

3. Solving Henssge equation using Solver

3.1. Set-up and operation of Solver (upper and lower panels in Fig. 1, Sheet 1 and Sheet 2 in SEF-1)

As the first approach to solving the Henssge equation, formulas were entered into a Microsoft Excel file (Supplementary Excel File 1 (SEF-1)) as shown with column (letter) and row (number) references in Fig. 1. This arrangement is a refinement of a spreadsheet approach previously reported in Japanese.[23]

To solve the equations using Solver, the add-in to Excel must first be installed. Then, the user makes entries into cells outlined in red as follows (overwrite entries of the starting example). Enter all observed variables (inputs) into cells C2–C5 for *Tr*, *Ta*, *W* and *CF*. A tentative guess at the value of *t* must be entered in C11. Here, the initial set of inputs (*Tr*, *Ta*, *W*, *CF*, *t*) = (30 °C, 20 °C, 70 kg, 1.2, 10 h) gave a value (−0.14344) for *Dq* in C10 (Spreadsheet shown in upper panel of Fig. 1).

Next, click the *Solver command* to display the *Solver Parameters dialog*, so that entries and operations are made to conduct calculations on column C as follows:

In the *Set Objective* box, click cell C10 or type C10, which displays entry "C10" for *Dq*.

Click *Value of*, then enter "0" ($Dq \rightarrow 0$)

In the *By Changing Variable Cells* box, click cell C11 or type "C11" to enter a tentative estimate for the postmortem interval (*t*).

Leave the *Subjects to the Constraints* box empty.

Click *Solver*, and if the *Solver Results dialog window* displays the message "Solver found a solution", press *OK*, which returns the user to the spreadsheet where the tentative estimate in C11 is replaced with a calculated *t* (14.54341 h as shown in lower panel of Fig. 1) that minimizes *Dq* to be close to 0. For practical use, the calculated value of *t* is rounded to one decimal place and reported in C12. In the case of an unsuccessful calculation, the reason is likely an inappropriate entry in the *Set Object* box and/or *By Changing Variable Cells* box or unintentionally creating meaningless constraints. After correcting any errors, click *Solver* again.

Because the iterative calculation is sensitive to the initial values, running Solver again after inputting a shorter or longer *t* will yield different values of *t* and *Dq*, but the difference (usually, on the order of

	A	B	C	D
1	Variable / Formula	Abbreviation		Unit
2	Rectal temperature	*Tr*	30	°C
3	Ambient temperature	*Ta*	20	°C
4	Body weight	*W*	70	kg
5	Corrective factor	*CF*	1.2	
6	Formula 1	*Qd*	0.581395	
7	Formula 2	*Qp*	0.724837	
8	Formula 3	*A*	1.25	
9	Formula 4	*B*	-0.05196	
10	Formula 6	*Dq*	-0.14344	
11	Postmortem interval	*t*	10	hr
12	Rounded *t*	*rt*	10	hr
13	Confidence interval	±*Δt*	2.8	hr

	A	B	C	D
1	Variable / Formula	Abbreviation		Unit / Code of formula
2	Rectal temperature	*Tr*	30	°C
3	Ambient temperature	*Ta*	20	°C
4	Body weight	*W*	70	kg
5	Corrective factor	*CF*	1.2	
6	Formula 1	*Qd*	0.581395	=LET(Tr,C2,Ta,C3,(Tr-Ta)/(37.2-Ta))
7	Formula 2	*Qp*	0.581395	=LET(A,C8,B,C9,t,C11,A*EXP(B*t)+(1-A)*EXP(A/(A-1)*B*t))
8	Formula 3	*A*	1.25	=LET(Ta,C3,IF(Ta<=23,5/4,10/9))
9	Formula 4	*B*	-0.05196	=LET(W,C4,CF,C5,-1.2815*(CF*W)^(-5/8)+0.0284)
10	Formula 6	*Dq*	6.8E-08	=LET(Qd,C6,QP,C7,Qd-QP)
11	Postmortem interval	*t*	14.54341	hr
12	Rounded *t*	*rt*	14.5	=ROUND(C11,1)
13	Confidence interval	±*Δt*	2.8	=LET(CF,C5,Qd,C6,IF(CF=1,IFS(Qd>0.5,2.8,Qd>0.3,3.2,Qd>0.2,4.5,TRUE,0),IFS(Qd>0.5,2.8,Qd>0.3,4.5,Qd>0.2,7,TRUE,0)))

Fig. 1. Spreadsheet for solving the Henssge equation to find the postmortem interval using the iterative program, Solver Add-in. The upper panel shows the spreadsheet before running Solver. The initial variables (*Tr*, *Ta*, *W*, *CF*) entered by the user and a tentative guess of *t* (10 h) are enclosed in red, and values calculated by formulas (*Qd*, *Qp*, *A*, *B*, *Dq*, *rt*, ±*Δt*) are denoted by blue characters.
The lower panel shows the spreadsheet after running Solver. *Qp* approached *Qd*, *Dq* became closer to 0, and an approximate solution (*t*) of 14.54341 h (C11) was obtained, the rounded value of which (*rt*) was 14.5 h (C12). Formulas are shown in Column D. For $Qd \leq 0.2$, the confidence interval (±*Δt*) will display "0″, which should be taken to mean that the result is unreliable rather than definitive. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

10^{-7} for *Dq*) is negligible in practical terms.

3.2. Excel formulas used in spreadsheet (Lower panel in Fig. 1, Sheet 2 in SEF-1)

The formulas were written using the built-in function LET, which works in Excel 365, Excel 2021 and Excel for the web. Formula 2 in C7 (*Qp*), for example, was

=LET(A,C8,B,C9,t,C11,A*EXP(B*t)+(1-A)*EXP(A/(A-1)*B*t))

Where the front part "LET (A,C8,B,C9,t,C11,)" was read as a ladder of pairs of names and referring cell addresses, namely (A,C8), (B,C9) and (t,C11), to assign a value calculated by formula 3 in C8 to A, that by formula 4 in C9 to B, and a value entered in C11 to *t*. Then, using these calculated or entered values, the last part "A*EXP(B*t)+(1-A)*EXP (A/(A-1)*B*t)" was calculated. The look of this part is the same as that of formula 2: $A \times \exp(B \times t) + (1 - A) \times \exp\left(\frac{A}{A-1} \times B \times t\right)$, and thereby one can easily confirm the logic of the calculation.

On the other hand, if one writes formula 2 in the usual way, it will be written as

=C8*EXP(C9*C11)+(1-C8)*EXP(C8/(C8-1)*C9*C11)

It is necessary to scrutinize both this formula and the referenced cells (C8, C9, C11) in order to confirm what is represented by formula 2.

However, the LET function needs more characters to construct a mathematical formula, which is a trade-off for understandability. As with formula 1, for example, " = LET (Tr,C2,Ta,C3, (Tr-Ta)/(37.2-Ta))" is longer than the usual formula "=(C2–C3)/(37.2-C3)". Thus, although we think that the LET function is helpful for novices, it might be redundant for some, and more importantly, it does not work in earlier versions of Excel (a formula including the LET function will be displayed as text only). Therefore, spreadsheets were also prepared in the usual way (Sheet 3 and Sheet 4 in SEF-1).

Additionally, the confidence interval for the postmortem interval (±*Δt*), which depends on *CF* (C5) and *Qd* (C6), was entered as determined by Henssge. For example, for $t = 8.4$ h and $\pm\Delta t = 2.8$ h, the actual postmortem interval would be considered to be between 5.6 and 11.2 h. Of note, Potente et al.[14,24] stated that this interval is valid for $Qd > 0.2$ when $Ta \leq 23$ °C, but only valid for $Qd > 0.5$ when $Ta > 23$ °C.

4. Solving Henssge equation using approximated solution by forward calculation

4.1. Use of spreadsheet for forward calculation (upper panel of Fig. 2, Sheet 1 in SEF-2)

In the first approach, *Ta* is assumed to be stable. However, this temperature usually varies to some extent during cooling of the body. A practical method for coping with this is to calculate *t* for the highest and lowest values of *Ta*.[3] In addition, considering the ambiguity of *CF*, it may be necessary to make calculations for two values of *CF*.[3] Taken together, *t* often needs to be calculated from 4 (2 × 2) set of variables,[3] but running Solver repeatedly for each combination is time consuming. Thus, we prepared another spreadsheet that can be used to approximate solutions for four sets of variables simply by entering observed variables (*Tr*, *Ta*, *CF*, *W*).

A calculation example is shown in upper panel in Fig. 2. In columns C to F, four sets of values (25 °C and 1.1, 25 °C and 1.3, 27 °C and 1.1, and

	A	B	C	D	E	F	G
1	Variable / Formula	Abbreviation					Unit
2	Rectal temper. (RT)	*Tr*	32	32	32	32	°C
3	Ambient temperature	*Ta*	25	25	27	27	°C
4	RT at death	*T0*	37.2	37.2	37.2	37.2	°C
5	Body weight	*W*	70	70	70	70	kg
6	Corrective factor	*CF*	1.1	1.3	1.1	1.3	
7	Formula 1	*Qd*	0.57377	0.57377	0.490196	0.490196	
8	Formula 3	*A*	1.111111	1.111111	1.111111	1.111111	
9	Formula 4	*B*	-0.05645	-0.04804	-0.05645	-0.04804	
10	Formula 7	*t*	11.7	13.75	14.45	17	hr
11	Rounded *t*	*rt*	11.7	13.8	14.5	17	hr
12	Confidence interval	±*Δt*	2.8	2.8	4.5	4.5	hr
13							
14		*t* (0 to 48 hr)	*Qp(t)*	*Qp(t)*	*Qp(t)*	*Qp(t)*	
15	Formula 2	0	1	1	1	1	
16		0.05	0.999961	0.999971	0.999961	0.999971	
17		0.1	0.999844	0.999887	0.999844	0.999887	
975		48	0.073952	0.110744	0.073952	0.110744	

	A	B	C	D
1	Variable / Formula	Abbreviation		Unit / Code of formula
2	Rectal temper. (RT)	*Tr*	32	°C
3	Ambient temperature	*Ta*	25	°C
4	RT at death	*T0*	37.2	°C
5	Body weight	*W*	70	kg
6	Corrective factor	*CF*	1.1	
7	Formula 1	*Qd*	0.57377	=LET(Tr,C2,Ta,C3,T0,C4,(Tr-Ta)/(T0-Ta))
8	Formula 3	*A*	1.111111	=LET(Ta,C3,IF(Ta<=23,5/4,10/9))
9	Formula 4	*B*	-0.05645	=LET(W,C5,CF,C6,-1.2815*(CF*W)^(-5/8)+0.0284)
10	Formula 7	*t*	11.7	=XLOOKUP(C7,C15:C975,$B15:$B975,,1)
11	Rounded *t*	*rt*	11.7	=ROUND(C10,1)
12	Confidence interval	±*Δt*	2.8	=LET(CF,C6,Qd,C7,IF(CF=1,IFS(Qd>0.5,2.8,Qd>0.3,3.2,Qd>0.2,4.5,TRUE,0),IFS(Qd>0.5,2.8,Qd>0.3,4.5,Qd>0.2,7,TRUE,0)))
13				
14		*t* (0 to 48 hr)	*Qp(t)*	
15	Formula 2	0	1	=LET(A,C$8,B,C$9,t,$B15,A*EXP(B*t)+(1-A)*EXP(A/(A-1)*B*t))
16		0.05	0.999961	=LET(A,C$8,B,C$9,t,$B16,A*EXP(B*t)+(1-A)*EXP(A/(A-1)*B*t))
17		0.1	0.999844	=LET(A,C$8,B,C$9,t,$B17,A*EXP(B*t)+(1-A)*EXP(A/(A-1)*B*t))
975		48	0.073952	=LET(A,C$8,B,C$9,t,$B975,A*EXP(B*t)+(1-A)*EXP(A/(A-1)*B*t))

Fig. 2. Another spreadsheet that instantaneously provides the estimated postmortem interval by forward calculation (upper panel of spreadsheet). Columns C, D, E and F show approximate solutions for 4 (2 × 2) sets of *Ta* and *CF* (25 °C&1.1, 25 °C&1.3, 27 °C&1.1, and 27 °C&1.3, respectively), with other variables (*Tr*, *T0*, *W*) held constant. For accommodating a series of *t* from 0 to 48 h at time intervals of 0.05 h and corresponding *Qp*(*t*), rows 15 to 975 were used, but only the first three and the last rows are shown. The lower panel shows the spreadsheet with the formulas in Column C.

27 °C and 1.3) were entered as *Ta* and *CF*, respectively, and values for other variables (*Tr* = 32 °C and *W* = 70 kg) were the same as in these columns. The results obtained by forward calculation were 11.7, 13.75, 14.45 and 17 h, respectively, which were rounded to 0.1 h (6 min) intervals (11.7, 13.8, 14.5 and 17 h, respectively).

4.2. Formulas for spreadsheet (lower panel in Fig. 2, Sheet 2 in SEF-2)

Schweitzer has been managing a trustworthy website since 2005,[16] and Schweitzer and Thali[17] reported that they achieved a more efficient approximation by forward calculation than by iteration. This spreadsheet is suited to forward calculation with fill-down operations. Thus, we prepared another type of spreadsheet based on forward calculations using the built-in function of Excel, XLOOKUP. The general algorithm is as follows.

Referring to a column with a series of *t* at intervals of 0.05 h from 0 to 48 h, a series of *Qp*(*t*) was generated in a different column (*Qp* (0), *Qp* (0.05), *Qp* (0.1), *Qp* (0.15), …, *Qp* (47.95), *Qp* (48)) in the forward calculation process. *Qp*(*t*) decreases monotonically from 1 to 0, and while *Qp* might happen to be exactly the same as *Qd*, such cases are very unlikely due to the double exponential decay nature *of Qp*(*t*). In virtually all cases, *Qd* would fall between two successive *Qp*(*t*) values, designated here as *Qp*(*j*) and *Q* (*j* + 0.05). That is, *Qp* (0) > *Qp* (0.05) > *Qp* (0.1) > … > *Qp* (*j* − 0.05) > *Qp*(*j*) > *Qd* > *Qp* (*j* + 0.05) > *Qp* (*j* + 0.1) > … > *Qp* (48). Then, " = XLOOKUP" performs a multitask operation: it looks up *Qp*(*j*) in the column with the series of *Qp*(*t*) and returns *j* from the column with the series of *t*.

The code is shown in the lower panel in Fig. 2. Column B is a series of *t* values (*t* = 0, 0.05, 0.1, 0.15, …, 48 h) in B15 to B975 (961 rows). Column C is a series of formulas for calculating *Qp*(*t*) from *t* in Column B for the same row. As shown in C15–C17, the first three *Qp*(*t*)s, for example, are

Qp(0):=LET(A,C$8,B,C$9,t,$B15,A*EXP(B*t)+(1-A)*EXP(A/(A-1)*B*t))

Qp(0.05):=LET(A,C$8,B,C$9,t,$B16,A*EXP(B*t)+(1-A)*EXP(A/(A-1)*B*t))

Qp(0.1):=LET(A,C$8,B,C$9,t,$B17,A*EXP(B*t)+(1-A)*EXP(A/(A-1)*B*t))

Of note, "$" is used in these formulas to make an absolute cell reference when filling-down. Absolute cell references can be made to a column by letter or a row by number.

The constants *A* and *B* are calculated using the formulas in C8 and C9, respectively, and are thus used as absolute references (C$8 and C$9). As Column B should be always referred to after filling rightward for *Qp (t)* in Columns D, E and F, "$" is added before the column name for B ($B15, $B16, $B17).

Then, an approximate solution can be found using

=XLOOKUP(C7,C15:C975,$B15:$B975,1) (7)

This formula searches a value of C7 (*Qd*) in the array of *Qp(t)* (C15: C975), looks up *Qp*(*j*) as a minimal value among *Qp*(*t*) > *Qd* under a match mode of "1" (expressed as " = XLOOKUP(,1)"), and returns a value in the cell of the same row of Column B ($B15:$B975), which is *j* (C10).

Here, *j* is indexed as "*t*" and means that a more precise approximated solution can be identified by Solver and should reside between *j* and *j* + 0.05 h. In the cells indexed as "*Rounded t*", *j* is rounded to the first decimal value using a built-in function " = ROUND(,1)". Using the rounded value for *j*, the more precise approximated solution should reside within *j* ± 0.05 h.

The website calculation treats rectal temperature at death as a variable instead of a fixed value of 37.2 °C.[16,17] Thus, it is also presented as a variable (*T0*) in this calculation.

Columns D, E, and F in Fig. 2 were made by repeated duplication of Column C.

Spreadsheets prepared without the use of the LET function are available as Sheet 4 and Sheet 5 in SEF-2.

4.3. Caveat about Henssge equation (Fig. 3, Sheet 3 in SEF-2)

When *Ta* is around 23 °C, the Henssge equation gives a somewhat inherent approximation during the early period after death due to the jump in constant *A* from 5/4 to 10/9 at this temperature. As illustrated in Fig. 3, contrary to the expectation that *t* would increase with increasing *Ta* because of decelerated cooling, *t* actually showed a reduction from 10.6 h (*Ta* = 23 °C; *A* = 5/4) to 9.4 h (*Ta* = 24 °C; *A* = 10/9). On the other hand, *t* increased from 10 h (22 °C) to 10.6 h (23 °C) for *A* = 5/4 and from 9.4 h (24 °C) to 10.1 h (25 °C) for *A* = 10/9 in accordance with expectations. As the postmortem interval increases, such incoherency disappears.

4.4. Formulas based on algorithm devised for Schweitzer website (Fig. 4, Sheet 2 in SEF-3)

On the trustworthy website by Schweitzer and Thali,[16,17] a series of absolute values of *Dq*(*t*), that is, |*Dq*(*t*)| = |*Qd* − *Qp*(*t*)| was generated at a time interval of 0.1 h, and the *t* value that produced a minimum |*Dq*(*t*)| was selected. This algorithm provides an approximation that is indistinguishable from that for the above-mentioned spreadsheet when adopting an interval of 0.05 h. Thus, an optional spreadsheet adopting an interval of 0.1 h was prepared based on this ingenious algorithm by using a built-in function ABS, which gives the absolute value, and XLOOKUP (Sheet 1 in SEF-3).

Fig. 4 shows formulas (Sheet 2 in SEF-3) that are comparable to those in the lower panel in Fig. 2. A spreadsheet prepared without the LET function is also available (Sheet 3 and Sheet 4 (code)).

4.5. Calculation error

Both SEF-2 and SEF-3 return a postmortem interval at a time interval of 0.1 h (6 min), and one would naturally expect the calculation error for this method to be within ±0.05 h (3 min). This degree of accuracy was achieved in SEF-2 by performing the forward calculations at a time interval of 0.05 h. In SEF-3, the same degree of accuracy could be achieved for forward calculation at a time interval of 0.1 h as described above because *Qp(t)* can be considered linear within a short timeframe of 0.1 h (*t*, *t* + 0.1). That is, for *Qd* > *Qp* (*t* + 0.05), then |*Qd* − *Qp*(*t*)| < |*Qd* − *Qp* (*t* + 0.1)| and for *Qd* < *Qp*

	A	B	C	D	E	F	G
1	Variable / Formula	Abbreviation					Unit
2	Rectal temper. (RT)	*Tr*	33	33	33	33	°C
3	Ambient temperature	*Ta*	22	23	24	25	°C
4	RT at death	*T0*	37.2	37.2	37.2	37.2	°C
5	Body weight	*W*	70	70	70	70	kg
6	Corrective factor	*CF*	1.2	1.2	1.2	1.2	
7	Formula 1	*Qd*	0.723684	0.704225	0.681818	0.655738	
8	Formula 3	*A*	1.25	1.25	1.111111	1.111111	
9	Formula 4	*B*	-0.05196	-0.05196	-0.05196	-0.05196	
10	Formula 7	*t*	10	10.6	9.35	10.1	hr
11	Rounded *t*	*rt*	10	10.6	9.4	10.1	hr
12	Confidence interval	±*Δt*	2.8	2.8	2.8	2.8	hr
13							
14		*t* (0 to 48 hr)	*Qp(t)*	*Qp(t)*	*Qp(t)*	*Qp(t)*	
15	Formula 2	0	1	1	1	1	
16		0.05	0.999983	0.999983	0.999967	0.999967	
17		0.1	0.999933	0.999933	0.999868	0.999868	
975		48	0.103211	0.103211	0.091744	0.091744	

Fig. 3. Example of using forward calculation spreadsheet introduced in Fig. 2 to find the postmortem interval. Columns C, D, E and F show estimated solutions for *Ta* = 22 °C, 23 °C, 24 °C and 25 °C, respectively, with other variables (*Tr*, *T0*, *W*, *CF*) held constant.

	A	B	C	D
1	Variable / Formula	Abbreviation		Unit / Code of formula
2	Rectal temper. (RT)	*Tr*	32	°C
3	Ambient temperature	*Ta*	25	°C
4	RT at death	*T0*	37.2	°C
5	Body weight	*W*	70	kg
6	Corrective factor	*CF*	1.1	
7	Formula 1	*Qd*	0.57377	=LET(Tr,C2,Ta,C3,T0,C4,(Tr-Ta)/(T0-Ta))
8	Formula 3	*A*	1.111111	=LET(Ta,C3,IF(Ta<=23,5/4,10/9))
9	Formula 4	*B*	-0.05645	=LET(W,C5,CF,C6,-1.2815*(CF*W)^(-5/8)+0.0284)
10	Formula 7	*t*	11.7	=XLOOKUP(0,C14:C494,$B14:$B494,,1)
11	Confidence interval	± *Δt*	2.8	=LET(CF,C6,Qd,C7,IF(CF=1,IFS(Qd>0.5,2.8,Qd>0.3,3.2,Qd>0.2,4.5,TRUE,0),IFS(Qd>0.5,2.8,Qd>0.3,4.5,Qd>0.2,7,TRUE,0)))
12				
13		*t* (0 to 48 hr)	|*Dq* (*t*)|	
14	Formula 2, *Qp* (*t*)	0	0.42623	=LET(Qd,C$7,A,C$8,B,C$9,Qp,A*EXP(B*$B14)+(1-A)*EXP(A/(A-1)*B*$B14),ABS(Qd-Qp))
15	|*Dq* (*t*)|=|*Qd* -*Qp* (t)|	0.1	0.426073	=LET(Qd,C$7,A,C$8,B,C$9,Qp,A*EXP(B*$B15)+(1-A)*EXP(A/(A-1)*B*$B15),ABS(Qd-Qp))
16		0.2	0.425618	=LET(Qd,C$7,A,C$8,B,C$9,Qp,A*EXP(B*$B16)+(1-A)*EXP(A/(A-1)*B*$B16),ABS(Qd-Qp))
494		48	0.499818	=LET(Qd,C$7,A,C$8,B,C$9,Qp,A*EXP(B*$B494)+(1-A)*EXP(A/(A-1)*B*$B494),ABS(Qd-Qp))

Fig. 4. Spreadsheet using forward calculation, prepared using the algorithm developed by Schweitzer and Thali[17] with formulas in Column C to find the post-mortem interval.

$(t + 0.05)$, then $|Qd - Qp(t)| > |Qd - Qp\ (t + 0.1)|$. Strictly speaking, $Qp(t)$ is not linear but concave upward for a shorter t or downward for a longer t. Therefore, when Qd is smaller and nearly equal to $Qp\ (t + 0.05)$ for a shorter t or when Qd is larger and nearly equal to $Qp\ (t + 0.05)$ for a longer t, these relationships are broken, and SEF-2 and SEF-3 give different results. For example, with a set of inputs ($Ta = 10$ °C, $Tr = 20$ °C, $T0 = 37.2$ °C, $CF = 1.2$, and $W = 25.783$ kg) for which $Qd \cong 0.3676471 > 0.3676454 \cong Qp\ (10 + 0.05)$, a fairly accurate approximated solution is obtained by the Solver of 10.049962 h ($Qp\ (10.049962) \cong 0.3676471$) and SEF-2 returned 10 h, but SEF-3 returned 10.1 h ($|Qd - Qp\ (10)| \cong 0.002227 > 0.002217 \cong |Qd - Qp\ (10 + 0.1)|$), and the calculation error exceed 0.05 h, though by a very slight length of time (0.050038 h). As the website uses the same algorithm, it also returned 10.1 h. However, the difference of 0.1 h was negligible given the confidence interval of the estimation ($\pm\Delta t$) being 2.8 h or more. Also, it seems quite unlikely that a set of variables that gives the different results would be inputted, and SEF-2 and SEF-3/website are expected to return the same approximate postmortem interval in practical cases.

5. Solving Henssge equation using Solver with additional columns that show predicted *Tr*

5.1. Additional columns to serve as guides for selecting initial tentative *t* (columns C and G in Fig. 5)

Fig. 5 shows the spreadsheet after running Solver (Sheet 2 in SEF-4) before running Solver in Sheet 1. This spreadsheet can deal with two sets of variables and contains two additional columns that show a series of *Tr* predicted for some *t* (0, 2, 4, …, 12, 15, 18, …, 36, 42, 48 h) by a forward calculation.[23] That is, Column G shows the series of *Tr* from a set of inputs (*T0*, *Ta*, *W*, *CF*) entered in Column C, and Column H shows a series of *Tr* from that entered in Column D. The forward calculation is based on the following equation:[23,24]

$$Tr = (T0 - Ta) \times Qp(t) + Ta, \tag{8}$$

which was derived from $Qd = \frac{Tr - Ta}{T0 - Ta} = Qp(t)$.

These *Tr* values may be referenced for entering guesses for *t* for using Solver. For example, among the series of *Tr* (Column G) predicted from a set of inputs ($T0 = 37.2$ °C, $Ta = 20$ °C, $W = 90$ kg, $CF = 1.2$) in Column C, the value nearest 29.5 °C was 29.2 °C at 21 h. Thus, running Solver from 21 h gave an approximate solution of about 20.1 h (C12, C13).

Minimum PMI (*mt*) shown in C17 and D17 is described in Section 6.

5.2. Estimation of rectal temperature at death (*T0*) for given postmortem interval (*t*) (columns D and H in Fig. 5)

The results of running Solver to estimate not postmortem interval (*t*) but rectal temperature at death (*T0*) are shown in Columns D and H. Considering the case in which *t* can be reasonably assumed to be 6 h by scene markers, and other measured parameters are $Tr = 30$ °C, $Ta = 18$ °C, and $W = 50$ kg, and assumptions are $T0 = 37.2$ °C and $CF = 1.4$, the measured *Tr* of 30 °C appears to be a little too low considering the timeframe and other variables. Indeed, running Solver in the usual way (choosing *t* as *Changing Variable Cells*) gives a rounded *t* (*rt*) of 11 h. Additionally, running Solver by choosing *T0* as the *Changing Variable Cells* with *t* (6 h) unchanged gives a *T0* of about 32.6 °C (D4), which is lower than the basic assumption of 37.2 °C. Thus, solving the Henssge equation in terms of *T0* for a given *t* might give an opportunity to notice abnormal or unusual rectal temperature at death (hypothermia as in this case or hyperthermia),[25] and its cause would warrant further investigation.

The formulas are shown in Sheets 3 and 4 in SEF-4, and spreadsheets prepared without the LET function are given in Sheets 5 to 8.

6. Reasonable estimation suggested by Potente et al. for longer postmortem interval (*t*)

6.1. Analytical solution for longer *t*

The first and the second terms of $Qp(t) = A \times \exp(B \times t) + (1 - A) \times \exp(\frac{A}{A-1} \times B \times t)$ (formula 2) are both

	A	B	C	D	E	F	G	H
1	Variable / Formula	Abbreviation			Unit		*Tr* (°C) predicted for	
2	Rectal temperature	*Tr*	29.5	30	°C	*t* (hr)	Column C	Column D
3	Ambient temperature	*Ta*	20	18	°C	0	37.2	32.6
4	RT at death	*T0*	37.2	32.56072	°C	2	37	32.1
5	Body weight	*W*	90	50	kg	4	36.4	31.2
6	Corrective factor	*CF*	1.2	1.4		6	35.6	30
7	Formula 1	*Qd*	0.552326	0.824135		8	34.7	28.8
8	Formula 2	*Qp*	0.552326	0.824135		10	33.8	27.7
9	Formula 3	*A*	1.25	1.25		12	32.9	26.6
10	Formula 4	*B*	-0.04028	-0.06166		15	31.5	25.2
11	Formula 6	*Dq*	-1.4E-09	1.22E-07		18	30.3	24
12	Postmortem interval	*t*	20.08109	6	hr	21	29.2	23
13	Rounded *t*	*rt*	20.1	6	hr	24	28.1	22.1
14	Confidence interval	±*Δt*	2.8	2.8	hr	27	27.2	21.4
15						30	26.4	20.9
16	If *Qd* < 0.2 (*Ta* ≤ 23°C) or < 0.5 (*Ta* > 23°C)					33	25.7	20.4
17	Minimum PMI	*mt*	45.5	29.7	hr	36	25	20
18						42	24	19.4
19						48	23.1	18.9

Fig. 5. Spreadsheet for finding the postmortem interval using Solver with additional Columns G and H, which display *Tr* predicted from (*Ta*, *T0*, *W*, *CF*) in Columns C and D, respectively. Both Columns C and D are generated after running Solver. In Column C, (*Tr*, *Ta*, *W*, *CF*) were entered (enclosed in red). As a guess for *t*, 21 h was entered in C11 (enclosed in green) because in the series of predicted *Tr* values in Column G, the value nearest to *Ta* (29.5 °C) was 29.2 °C at 21 h. Then, *t* was calculated to be 20.08109 h by Solver. For Columns D and H, see text (Estimation for *T0* for given *t*).
C17 and D17 accommodate formula 11 for a longer *t*. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

exponential decay functions (B < 0). Since A/(A-1) is 5 ($Ta \le 23$ °C) or 10 ($Ta > 23$ °C), the second term approaches 0 much more rapidly than the first term. This means that as the postmortem interval (*t*) increases, the second term becomes negligible. For a longer *t*, the Henssge equation can thus be approximated as

$$Qd = Qp(t) \cong A \times \exp(B \times t). \tag{9}$$

This equation can be analytically solved to give:

$$t \cong \ln\left(\frac{Qd}{A}\right) \div B \tag{10}$$

6.2. Minimum time since death (minimum postmortem interval) for longer t

Potente et al.[24] suggested that for a body whose *Qd* is smaller than 0.2 ($Ta \le 23$ °C) or 0.5 ($Ta > 23$ °C), a reasonable estimation of *t* should be the time at which *Qp*(*t*) reaches 0.2 or 0.5, respectively, regardless of the actual value of *Qd*. They regarded this *t* as the minimum time since death for *Tr* to either reach or closely approximate equilibrium with ambient temperature.

The minimum time since death, which is termed the minimum postmortem interval (*mt*) in this technical note, can be calculated by running Solver, targeting 0.2 or 0.5 for *Qp*(*t*) (formula 2) by changing *t* (*Qp* → 0.2 or 0.5). As with the forward calculation, the minimum *Qp*(*t*) that is larger than 0.2 or 0.5 and the associated *t* value can be found using XLOOKUP with a match mode of "1" (maximum *Qp*(*t*) that is smaller than 0.2 or 0.5 with a match mode of "2"). However, an approximate value of *mt* can be instantaneously obtained using formula 11:

$$mt \cong \ln(0.16) \div B \text{ for } Ta \le 23^\circ C$$

$$mt \cong \ln(0.45) \div B \text{ for } Ta > 23^\circ C \tag{11}$$

where *ln* (*Qd*/*A*) (formula 10) = *ln* (0.2 ÷ 5/4) = *ln* (0.16) ≅ −1.8326 and *ln* (0.5 ÷ 10/9) = *ln* (0.45) ≅ −0.7985.

As an example, for *Tr* = 20.2 °C, *Ta* = 19.9 °C, *W* = 87 kg, and *CF* = 1.1, the values of *Qd* and *t* were calculated to be 0.01734 and 48 h, respectively, by forward calculation (SEF-2 or SEF-3).[24] However, *Qp* (48) was 0.1396, meaning that *Tr* did not yet decrease to 20.2 °C at this time, and thus *t* was calculated using Solver (SEF-4). The calculated value was 93.7 h, but *mt* was (−1.8326) ÷ (*B* = −0.04567) ≅ 40.1 h, which was in accordance with the value of 39.9 h obtained using a different calculation method.[24]

Formula 11 is incorporated in the spreadsheet using Solver (Fig. 5, SEF-4). It is also incorporated in the spreadsheets by forward calculation as additional sheets (Sheets 6–9 in SEF-2 and Sheets 5–8 in SEF-3).

7. Discussion

Based on a time differential equation by Marshall and Hoare:[26]

$$\frac{dQ(t)}{dt} = B \times Q(t) - B \times \exp\left(\frac{A}{A-1} \times B \times t\right), \tag{12}$$

Henssge[18] was able to find a reasonable way to fix constants A and B and thereby formulated an equation that was expressed as a set of formulas 1-5 (the Henssge equation, also called the Marshall-Hoare-Henssge model[26]). He then devised a graphical method to solve the equation for estimating the postmortem interval (the Henssge nomogram method). Although the nomogram method has limitations[25,27] it has been accepted in many countries as a reliable, practical method in case work.[28] The equation can also be solved by computation, and we propose use of Microsoft Excel, a program that many forensic practitioners are familiar with. The Excel formulas used in the present paper, including the version without the LET function, are included as SEFs and are described at the end of this paper.

Schweitzer and Thali[17] reported that they have received numerous

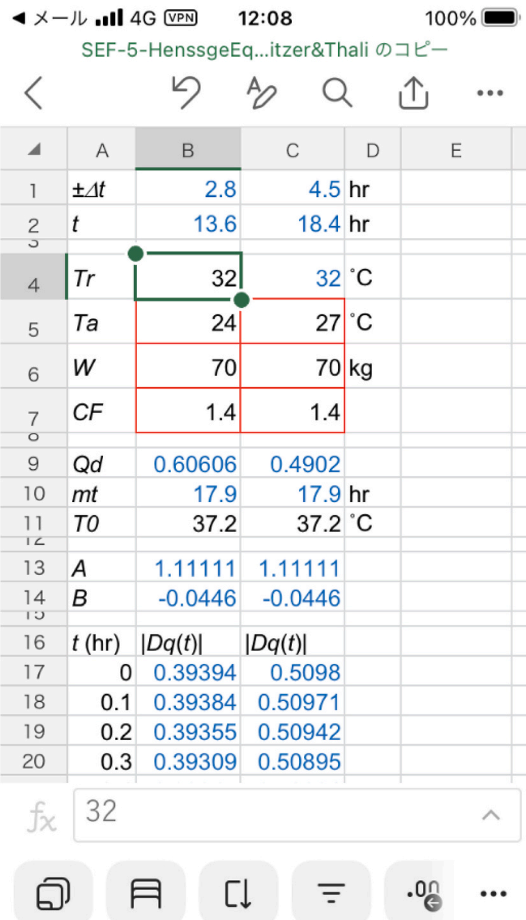

Fig. 6. Screenshot of modified version of spreadsheet for finding the postmortem interval based on the algorithm developed by Schweitzer and Thali[17] for use on a smartphone. The number of columns (inputs are enclosed in red) was reduced to two to accommodate the smaller screen size of a smartphone. Upon entering *Tr* in the first column, the same value appears in the second column.
In Column C, *mt* (minimal postmortem interval, 17.9 h) is shorter than *t* (18.4 h) because *Qd* (0.4902) is smaller than 0.5. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

requests to explain how they achieved efficient approximation for the Henssge equation. This suggests that most interest in their website is from experts in computation who do not need the code to understand the solution strategy. In this technical note, however, the code is shown using a built-in function FORMULATEXT to display the formulas used in cells in the SEFs, so that even users who do not have much experience in computation can understand and confirm the solution strategy and algorithms.

The solution strategy of the first type of spreadsheet was iteration. Schweitzer circumvented iteration and adopted the use of forward calculation to construct the website because writing an iteration program would be a demanding task.[17] However, when using Excel spreadsheets, one can easily perform iteration by simply running an add-in program, Solver.

Repeatedly running Solver can be tedious. Thus, a method based on forward calculation was developed to give an approximate time upon entering inputs. Spreadsheets (SEF-2 and SEF-3) were prepared using two algorithms, one of which (SEF-3) was originally devised for the website by Schweitzer. Both SEF-2/SEF-3 can handle four set of variables in the same screen and, together with simultaneous approximation, one can effortlessly obtain postmortem interval estimates for different values of ambient temperature (*Ta*) and empirical corrective factors (*CF*).

Any of these SEFs can be freely customized to fit user requirements. Two of the authors (NS and NY), for example, are using a modified version (SEF-5) of SEF-3 on a smartphone (Fig. 6). The reason why SEF-3 was chosen as a prototype is that it is half the size of SEF-2 and is suited to the smaller screen of a smartphone. In this regard, Neithiya et al.[29] who reported the usefulness of the Henssge equation in tropical environmental conditions encouraged the development of smartphone-based postmortem interval calculators.

8. Conclusion

Aside from the commercial software by Henssge, the website managed by Schweitzer is virtually the only free, trustworthy computational method for applying the Henssge equation to case data at present. Excel spreadsheets described in this technical note add one more option. We hope that the SEFs will be useful for forensics practitioners, including novices, who intend to use the Henssge equation, users of nomograms who wish to transition to computation, or users who intend to continue to use nomograms at the scene but who wish to introduce computation in situations suited for computation, such as offices and autopsy observation rooms.

Declaration of competing interest

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jflm.2023.102634.

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