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Comparison Method Between the Finite Element Method and the Henssge Model Method in Estimating the Time of Death

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Abstract

Estimating the time since death (TSD) is a fundamental aspect of forensic investigations, as it provides crucial information for reconstructing events leading to a person's death. Traditional methods, such as the Henssge model, estimate TSD based on postmortem body cooling but often struggle with complex environmental conditions. This study compares the Henssge model with the Finite Element Method (FEM), a numerical approach that simulates heat transfer mechanisms like conduction, convection and radiation. Using MATLAB, the accuracy of both methods was evaluated based on five forensic cases analysed by Mall and Eisenmenger (2005). Results indicate that FEM consistently provides more precise estimates, particularly in scenarios involving sudden temperature changes, clothing insulation and body repositioning. Statistical error analysis further supports FEM's advantages, with significantly lower mean absolute error (MAE) and root mean square error (RMSE) compared to the Henssge model. These findings confirm that FEM is a more reliable alternative for forensic time since death estimation and offers improved accuracy in real-world forensic applications.

1. Introduction

Estimating the time since death (TSD) is a crucial component of forensic investigations and provides important details for reconstructing the sequence of events leading to a person's death. Traditionally, forensic pathologists have relied on various physiological indicators such as rigor mortis (stiffening muscles), livor mortis (postmortem lividity and algor mortis (postmortem body temperature changes) to estimate TSD [1]. Algor mortis has been one of the most extensively researched. The most popular method in forensic science for calculating TSD by taking postmortem body temperature readings is the Henssge model, created based on Newton's Law of Cooling [2]. Despite its simplicity and practicality, this model has significant limitations in complex forensic cases where environmental and anatomical factors affect the cooling process [3], [4].

In order to overcome these limitations, computational methods like the Finite Element Method (FEM) have been developed to more precisely simulate heat transmission in the human body [5]. Numerous influencing elements, such as body mass, clothing, environmental conditions and body position, are taken into account while solving heat transfer equations using FEM, which is a numerical technique that is frequently used in physics and engineering [6]. Unlike the empirical Henssge model, FEM can simulate postmortem temperature decrease in more detail by incorporating conduction, convection and radiation [7]. Advances in forensic medicine have demonstrated that FEM has the potential to overcome many of the inaccuracies associated with traditional models, as it adapts to various forensic scenarios, including non-standard cooling conditions [8]. However, despite its benefits, FEM necessitates validation against actual forensic case data and substantial computational resources [9].

The precision of forensic time estimation is important since mistakes in TSD calculations might result in erroneous legal conclusions that impact criminal investigations and court proceedings [10]. The Henssge model is widely used because it is easy to apply. However, it assumes that cooling conditions remain constant, which rarely exists in actual forensic investigations. Cooling rates can be greatly impacted by variables including clothing, air movement and changes in the surrounding temperatures, which reduces the model's dependability in dynamic situations [11]. However, because FEM can replicate complicated thermal conditions and body interactions with the environment, it has been suggested as a more reliable option. To evaluate whether FEM offers a significant improvement over the Henssge model, a thorough comparison of the accuracy and error margins between these two option approaches is still required.

Comparing the accuracy of the FEM and the Henssge model in estimating the time since death is the main objective of this study. Specifically, the study aims to analyse the error between these approaches in various body and environmental circumstances, such as exposure to heat sources, body composition, and clothing materials. Additionally, this study seeks to determine whether FEM offers forensic applications as a more reliable and adaptable substitute. This study is important as it contributes to the ongoing refinement of forensic methodologies and enhances the reliability of TSD estimation. This study's assessment of the effectiveness of FEM concerning the Henssge model can help forensic pathologists choose the best approach for various forensic situations. Last but not least, increasing the precision of forensic time estimation might enhance criminal investigations, support legal proceedings and minimize wrongful convictions.

2. Methodology

This section introduced the methods and techniques to solve the problem of estimating the time since death with different scenarios studied by [12] and their accuracy will be analyzed based on the margin error calculated. The study aims to determine which method provides higher accuracy under different circumstances. By integrating numerical simulation with empirical validation, this study evaluates the reliability of both methods and highlights their strengths and limitations in forensic applications, which will be explained further in the Result and Discussion section later.

2.1 Related Data

This study will analyse how [12] uses the Finite Element Method (FEM) and the Henssge model to solve the estimation of the time since death, t_d in five different scenarios that include parameters like body insulation due to clothing, body positions and physical and environmental conditions.

2.2 Finite Element Method

The Finite Element Method (FEM) is a numerical technique for solving partial differential equations, particularly in heat transfer problems. In the context of postmortem cooling, the human body is divided into smaller sections, known as elements, where each element's temperature can be approximated using mathematical functions. The FEM provides an estimate of the time since death based on the cooling process by solving the heat conduction equation iteratively across these elements.

2.2.1 Governing Equation

The mathematical foundation of the model is based on the heat conduction equation in [5] derived from Fourier's law and the principle of energy conservation:

$$c\rho\frac{\partial T}{\partial t} - k\Delta \mathrm{T} = 0 \tag{1}$$

where;
c is the specific heat capacity
ρ is the density
$\frac{\partial T}{\partial t}$ is the time derivative of temperature
k is the thermal conductivity
T is the temperature field
$\Delta \mathrm{T}$ represents the second-order spatial derivative, indicating heat flow due to temperature gradients.
The Finite Element Method (FEM) simplifies this equation by breaking the body into discrete elements and solving the heat transfer for each element.

2.2.2 Model Implementation

The human body is modelled as a three-dimensional structure divided into various tissue compartments, such as skin, fat, tissue, bone and internal organs. The initial conditions assume a core body temperature of approximately 37 °C, which gradually decreases toward the surface and eventually matches the ambient temperature. The boundary conditions consider different modes of heat loss, including conduction, convection, radiation and internal power dissipation. For heat transfer through conduction, the Finite Element Method (FEM) directly solves them using equation (1). The heat transfer due to convection follows:

$$Q'_C = h(T_S - T_E) \tag{2}$$

where $\boldsymbol{Q'_C}$ represents convection heat transfer, $\boldsymbol{h}$ represents the convection coefficient where it assumes the mean value in natural convection of $\boldsymbol{h}$ = 3.3 $\boldsymbol{W/(m^2}$°C), $\boldsymbol{T_S}$ is the body surface temperature and $\boldsymbol{T_E}$ is the environmental temperature. The radiation heat loss is modelled using the Stefan-Boltzman equation:

$$Q'_R = \varepsilon\sigma A(T_S^4 - T_E^4) \tag{3}$$

where $\boldsymbol{\varepsilon}$ is the dimensionless emissivity of the radiating surface, $\boldsymbol{\sigma}$ is the Stefan-Boltzmann constant, which is ($\boldsymbol{5.67x10^{-8}W/(m^2K^4)}$), $\boldsymbol{A}$ is the radiating surface area while $\boldsymbol{T_S}$ and $\boldsymbol{T_E}$ are the absolute temperatures of the body's surface and environments. To validate the FEM approach, simulation results are compared against case studies and discrepancies are analysed to refine model parameters.

2.2.3 Flowchart of the Finite Element Method (FEM)

Fig. 1 shows the flowchart on how the FEM was implemented to solve the estimation of time since death.

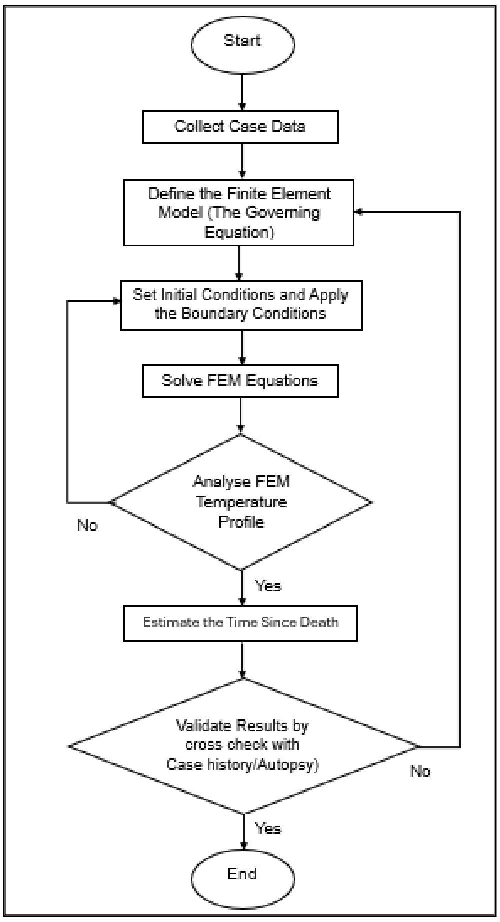

Fig. 1 Flowchart of the Finite Element Method (FEM)

2.3 Henssge Model

Henssge's model is a method that estimates the time of death due to its simplicity and empirical validation. It is also known for its graphical solution, the Henssge nomogram [13].

2.3.1 Governing Equation

The Henssge model is a widely used empirical method for estimating the time since death based on body cooling rates. It relies on the exponential cooling equation introduced by Marshall and Hoare in 1962 and later refined by [14]. The equation for the cooling process is:

$$\frac{T_r - T_a}{37.2 - T_a} = 1.25e^{Bt} + 0.25e^{5Bt} \tag{4}$$

where;
T_r is the rectal temperature at the time, t
T_a is the ambient temperature
B are cooling coefficient that depends on body weight
Since B varies with body weight, it is calculated using:

$$B = -1.2815m^{-0.625} + 0.0284$$

where m is the body weight in kilograms.

2.3.2 Estimation of the time since death, *t*

There are some optional processes to solve the estimation of time since death since the Henssge cooling equation cannot be directly cannot be solved explicitly for ***t***.

2.3.2.1 Numerical Solution Using Newton-Raphson Method

Since the Henssge cooling equation cannot be directly cannot be solved explicitly for ***t***, numerical methods such as the Newton-Raphson method are used for approximation. The iterative formula applied is:

$$t_{n+1} = t_n - \frac{1.25e_n^{-Bt} - 0.25e_n^{-5Bt} - \frac{T_r - T_a}{37.2 - T_a}}{-1.25Be^{-Bt_n} + 6.25Be^{-5Bt_n}} \tag{5}$$

where t_{n+1} is the improved estimate of t and t_n is the current estimate of the solution. This iterative process refines the estimation of t until convergence is achieved. This numerical problem can be solved in Python or MATLAB.

2.3.2.2 Henssge Nomogram

Forensic practitioners commonly use the Henssge nomogram to quickly estimate the time since death. The estimation process involves
Step 1: Identifying the rectal temperature
Step 2: Drawing a line through the ambient temperature to the body mass curve
Step 3: Finding the corresponding postmortem interval
Step 4: Applying correction factors for clothing, body position, and environmental influences as described in [13]'s studies.

2.3.3 Flowchart of the Henssge model

Fig. 2 shows how the Henssge model solves the estimation of time since death (TSD) by following this flowchart.

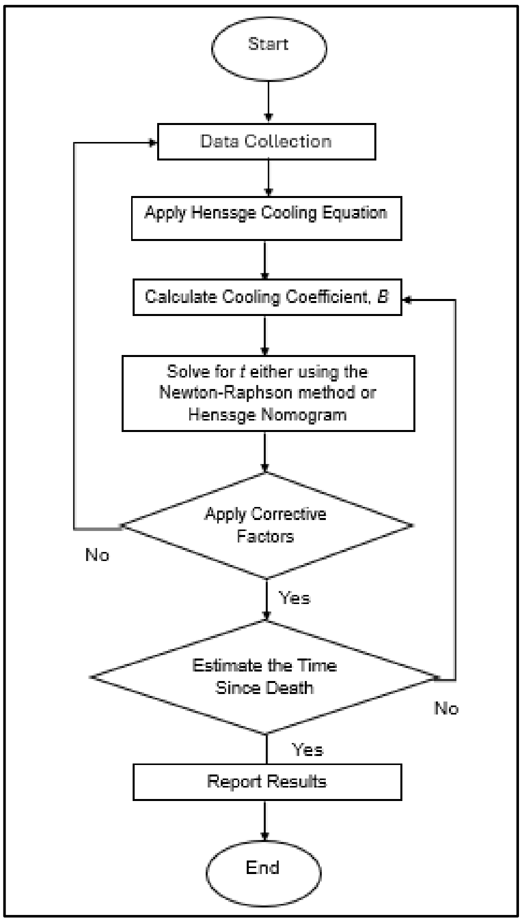

Fig. 2 Flowchart of the Henssge model

3. Results and Discussion

3.1 Case Studies and Comparative Analysis

Five forensic cases were analysed using both Finite Element Method (FEM) and the Henssge model that [12] has studied. Each case involved different circumstances, such as differences in body posture, clothing and surrounding temperature. Actual forensic findings and the estimated time since death (TSD) derived from both approaches were constructed, including calculating the margin error between them. The results are summarized in Table 1

Table 1 Comparison error analysis of the estimation of time since death, t_d between Finite Element Method (FEM) and the Henssge Model towards actual autopsy estimation

Case	Autopsy estimates t_d (hours)[12]	FEM estimates t_d (hours)	Henssge estimates t_d (hours)	Absolute Error (AE) (FEM)	Absolute Error (AE) (Henssge)	Relative Error (RE) (FEM)	Relative Error (RE) (Henssge)
1	4.25	5.25	10.50	1.00	6.25	23.53	147.06
2	7.50 - 8.00	7.75	9.80	0.00	2.05	0.00	26.45
3	11.50	11.00	12.70 - 14.00	0.5	1.85	4.35	16.09
4	7.25 - 8.25	8.00	9.30	0.25	1.55	3.23	20.00
5	25.00 - 25.5	25.00	> 35.00	0.25	9.75	0.99	38.61

	Finite Element Method	Henssge Model
Mean Absolute Error (MAE)	0.40	4.29
Root Mean Square Error (RMSE)	5.37	0.52

The FEM demonstrated a significantly smaller error margin compared to forensic estimates, while the Henssge model showed significant variations. For example, in Case 1, where a 23-year-old male was discovered inddors at 20°C, the Henssge model overestimated the time since death (10.50 hours) compared to forensic findings (4.25 hours), resulting in an error of 147.06%. Meanwhile, FEM produced an estimation of 5.25 hours, nearly matching the forensic findings.

Comparably, FEM calculated the time since death in Case 5, where a 60-year-old man was discovered in a room at 25°C, to be roughly 25.00 hours, which was in line with the forensic results. The Henssge model, on the other hand, anticipated a far longer time, which is more than 35 hours, and was very different from what was actually observed. These differences demonstrate the Henssge model's shortcomings when used in challenging real-world situations.

3.2 Factors Influencing the Accuracy of Each Method

3.2.1 Sudden changes in Ambient Temperature

The Henssge model's dependence on a fixed cooling rate, which cannot capture sudden changes in the surrounding temperature, is one of its main limitations. The Henssge model calculated a time since the death of roughly 8:00 p.m. in Case 3, where the body was first inside a warm vehicle before being exposed to an outdoor temperature of 5°C. In contrast, FEM included stepwise cooling and produced a more accurate estimate that was closer to 9:30 p.m., which was aligned with the witness reports. This suggests that FEM offers more flexibility for dealing with sudden temperature changes.

3.2.2 Influence of external Irradiation

The Henssge model does not account for external heat sources like sun or radiant heating and instead assumes a constant cooling process. This oversight may result in significant errors when estimating time since death (TSD). Although there was no direct sun exposure in any of the cases examined, FEM has the benefit of considering irradiation effects, which makes it a more trustworthy method in this situation.

3.2.3 Effect of Body Composition and Clothing

The Henssge model only uses correction factors to approximate heat dissipation, which is influenced by body mass and insulation from clothes. Nevertheless, the complexity of heat retention in various body types and garment layers is not fully captured by these considerations. The Henssge model projected the victim's time of death in Case 2, where she was fully clothed in many layers, at around 2:00 p.m.. At the same time, FEM took the garment insulation into consideration and predicted a more precise time of about 4:15 p.m., which was subsequently confirmed by forensic evidence.

3.2.4 Body Movement and Position Changes

In Case 2, where the body was moved from a face-down to a face-up position, Finite Element Method (FEM) was able to account for the resulting variations in heat loss, producing a more accurate estimation than the Henssge model. In Case 5, where the victim's clothing was partially displaced, FEM accounted for the localized heat retention, producing a more accurate estimation of TSD.

3.3 Error Analysis

Statistical error metrics such as mean absolute error (MAE) and root mean square error (RMSE) were computed in order to further measure the accuracy of both approaches. The findings, which are shown in Table 1, show that FEM continuously performed more accurately than the Henssge model. The Henssge model had a much larger MAE value, which is 4.29 hours, than FEM, which had an MAE of only 0.40 hours. Similarly, the FEM's RMSE was 0.52 hours, while the Henssge model was 5.37 hours, which was significantly higher.

These statistical results highlight the accuracy and constancy of FEM's estimations, demonstrating its dependability. The errors in the Henssge model were particularly pronounced in cases including clothing, sudden temperature changes and positional shifts, showing the model's errors are noticeable as it does not account for properly.

4. Conclusion and Recommendations

This study successfully achieved its objective of comparing the accuracy and reliability of the Finite Element Method (FEM) and the Henssge model in estimating the time since death based on [12]. The results, based on five real forensic cases, showed that FEM consistently provided more precise estimates than the Henssge model, which struggled with cases involving sudden temperature changes, clothing and body positioning. FEM accounted for complex heat transfer mechanisms like conduction, convection and radiation. This makes this method become a more reliable tool for forensic investigations. The statistical analysis further confirmed this, with FEM showing significantly lower errors than the Henssge model. This highlights the potential of FEM as the best alternative for forensic time since death estimation.

For future research, it is recommended to incorporate additional factors, such as postmortem biochemical changes, humidity levels and wind effects in order to improve the accuracy of time since death estimation. Furthermore, while this study focused on comparing FEM with the Henssge model, future studies should explore how FEM compares to other advanced methods, such as Bayesian inference models and hybrid approaches, in order to determine the most effective forensic tool. By implementing these improvements, forensic science can continue to develop more accurate and reliable methods, ultimately strengthening criminal investigations and the justice system.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The author confirm contribution to the paper as follows: ***study conception and design:*** *Mazaya Wani Yahya, Mahathir Mohamad;* ***solve the governing equation:*** *Mazaya Wani Yahya, Mahathir Mohamad;* ***data collection:*** *Mazaya Wani Yahya, Mahathir Mohamad;* ***analysis and interpretation of results:*** *Mazaya Wani Yahya, Mahathir Mohamad:* ***draft manuscript preparation:*** *Mazaya Wani Yahya. All authors reviewed the results and approved the final version of the manuscript.*

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