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Post-Mortem Interval Estimation Using Newton's Law of Cooling and the Henssge Model

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Abstract

The estimation of post-mortem interval (PMI) is an essential part of forensic investigation, as it helps to reconstruct events related to death and make decisions about medico-legal matters. The use of temperature-based techniques, particularly approaches based on algor mortis, is often applied in the early post-mortem phase due to its quantitative and objective nature. However, the accuracy of PMI estimation remains an issue, as body cooling is regulated by environmental factors and personal physiological characteristics. This study aimed to compare Newton's Law of Cooling and the Henssge approach in estimating PMI under controlled conditions over a range of observation times. Both methods were applied to documented post-mortem temperature data, and PMI estimates were evaluated using absolute error and mean absolute error (MAE). The results showed that Henssge method is slightly more accurate in the early post mortem period but Newton Law of Cooling is more consistent and less prone to increase its errors over the longer post-mortem periods. Therefore, these results imply that the accuracy of temperature-based PMI estimates changes with the post-mortem interval, and rather than depending entirely on one method, the expected time since death should be used to guide method selection.

1. Introduction

The proper estimation of the PMI is one of the foundations of forensic science since it has a crucial role in the reconstruction of death timelines, the validation of alibis, and the provision of essential assistance in criminal investigations and legal trials. The practical problem is that it is necessary to develop stable procedures of determining the time of death, when environmental conditions and body composition and situational factors, such as clothing and humidity, influence the cooling process. Traditional indicators like rigor mortis often fail to provide precise estimates, especially when environmental conditions are dynamic or when the post-mortem interval extends beyond a few hours.

The two primary approaches used to estimate PMI are grounded in distinct theoretical and empirical paradigms. The theoretical approach, based on Newton's Law of Cooling, models the rate of body temperature decline relative to the ambient temperature through an exponential decay function. Alternatively, the Henssge model, which is an empirical approach developed within the context of forensic science, includes such correction factors as the body mass, clothing and environmental conditions, thus being more flexible in real-life forensic applications.

While both methods are widely used, a systematic and quantitative comparison of these models, particularly across different environmental conditions, remains insufficiently explored. However, there is a great gap in the literature that supports these models in comparison to actual forensic cases, particularly in tropical or high-humidity conditions when ambient temperature and water content play a crucial role in determining the algor mortis rate, which refers to the cooling process of the human body after death [1][2][3].

This paper aimed to fill a critical gap in forensic pathology by accomplishing two main aims. First, it will determine the postmortem interval of real-life forensic cases using the Newton Law of Cooling and the Henssge model, thus measuring the effectiveness of both methodology in the field of forensics. Second, the study compared the time-of-death estimates of these two methods and evaluates them in reference to each other in a real situation of a forensic context.

The introduction part provided the necessary background, defines the research problem, outlines the research goals, and identifies the research gap. The methodology outlines the simulation approach adopted and includes the datasets utilized to validate the simulation, which will consist of historical cooling records and real case files. Results and Discussion section otherwise explained the findings, comparing the performance of the two methodological alternatives in a set of conditions. Lastly, the conclusion is where the key findings are summarised, the general implications of the study are discussed, and recommendations on future studies are provided in the field.

2. Methodology

This section describes the data source, mathematical models, numerical implementation, and statistical methods used to estimate the post-mortem interval and evaluate the accuracy of Newton's Law of Cooling and the Henssge model.

2.1 Data Collection

In this study, post-mortem temperature measurements from executions conducted in a controlled prison environment, as reported in [4], were used. The time of death is accurately recorded as 8:15 a.m. The rectal temperature measurements were also taken at fixed intervals. The ambient temperature was constant, making the dataset highly suitable for estimating PMI methods based on temperature decay. It also utilized the dataset in this study to ensure that methodological uniformity is achieved in the process of comparing the Newton Law of Cooling and the Henssge approach in the context of both the early and extended post-mortem periods.

2.2 Newton's Law of Cooling

Newton's Law of Cooling, which explains the rate at which a body loses heat to its surroundings, is widely utilized in physics-based estimates of time since death. The model assumes that the rate of change of body temperature is proportional to the difference between the body temperature and the ambient temperature [5].
The law is governed by the differential equation

$$\frac{dT}{dt} = -k\left(T - T_a\right) \tag{1}$$

where:

- $T(t)$: rectal temperature at time t,
- T_a : constant ambient temperature,
- k : cooling constant (dependent on body and environmental properties).

The solution of this differential equation produces [5]

$$T(t) = T_a + \left(T_0 - T_a\right)e^{-kt} \tag{1.1}$$

The study will use 37.2°C as the body's initial temperature since this represents the average core temperature just before death [6]. A straightforward experiment will involve setting one temperature throughout the scene and applying it to various hypothetical body temperatures reported later at different sites. Next, the variables are put into the equation to find the cooling constant k, using both rearrangement and logarithms.

2.3 Henssge Model

An empirically modified procedure that is applied to forensic practice to assess PMI using post-mortem body cooling is the Henssge model. The model is based on classical exponential cooling theory but with some modifications that consider the body mass and clothing and environmental conditions hence enhancing application in actual forensic case.

2.3.1 Governing Equation

The Henssge method of the cooling behaviour explains the cooling characteristics based on a normalized temperature equation, which was derived using the exponential cooling theory. The method is based on the classical cooling framework introduced by Marshall and Hoare (1962) and subsequently refined through empirical forensic studies [7]. The governing equation of the Henssge cooling model is expressed as

$$\frac{T - T_a}{37.2 - T_a} = 1.25e^{Zt} - 0.25e^{5Zt} \tag{2.0}$$

where:

- T : rectal temperature at time t
- T_a : the ambient temperature
- Z : the cooling constant.

The cooling constant Z is calculated using the following empirical formula

$$Z = -1.2815 \cdot \left(f \cdot M^{-0.625}\right) + 0.0284 \tag{2.1}$$

where:

- f : correction factor based on clothing and environmental conditions
- M: body mass in kilograms.

f in this study is the correction factor. The value of f was put at 1.0 when dealing with unclothed (nude) bodies and 1.2 when dealing with clothed bodies as dictated by normal forensic practice. Body mass ,m was directly obtained out of the data and was (50 kg - 60 kg) representing the range of individual body size of the subjects. This enables the Henssge model to capture the variation in insulation effects and thermal inertia which are a great contributor to post-mortem cooling behavior by the inclusion of the body mass as well as the correction factor.

2.4 Estimation of the Post-Mortem Interval

The PMI was estimated using numerical techniques because the Henssge cooling equation cannot be explicitly solved for time t. In particular, it is impossible to solve the PMI explicitly since the governing equations cannot be isolated from the time variable; instead, computational approximation techniques must be used [3][8]. Therefore, an iterative numerical approach was employed to determine the value of time that minimised the discrepancy between the measured rectal temperature and the estimated temperature predicted by the model. This procedure enabled the estimation of PMI through successive approximations until convergence was achieved, allowing a consistent comparison with PMI values obtained using the Newton's Law of Cooling.

In forensic practice, the Henssge method may also be applied using the Henssge model, which provides a graphical approach for PMI estimation. This process requires the measurement of the rectal temperature, determination of the related body mass curve and by a line between the ambient temperature and the measured body temperature. Appropriate correction factors were applied to the effects of clothing, position of the body, and ambient conditions on the cooling of a corpse after death and PMI estimation.

2.5 Computational Implementation and Visualization Using Python

The computations in this study will be done with Python because of its flexible nature, its open-source, and the powerful scientific libraries it includes [9] to find temperature changes, Newton's Law of Cooling is applied in Python by using the analytical equation for cooling, which lets us change the cooling constant (k) and the ambient temperature (T_a). Graphs can make temperature changes evident, which helps interpret when someone might have died. As the Henssge approximation does not have an explicit answer for time (t), we will calculate it with Python's numerical tools. Certain loops will run through different t values to improve the match of both equations while including both sizes, additional factors, and the temperature around the body. Seeing the model results following real or case data can improve understanding of how well the models work and their parameters' sensitivity. Using computational tools reduces errors, makes exploring data several times easier, and represents the outcomes.

2.6 Error Analysis and Correlation Analysis

Both methods of estimating the PMI are tested in terms of absolute error, which can be defined as absolute value of the difference between estimated PMI and actual PMI. The overall performance of each method is evaluated using the MAE, which represents the average of the absolute errors across all observations. In order to study the effect of the error in estimation with increasing post-mortem interval, two different observation times (early post-mortem and extended post-mortem) are analysed, 12:00 p.m. and 8:00 p.m. This method allowed to compare the accuracy of the Classic Newton cooling method and the Modified Henssge method at varying post-mortem duration.

SPSS is used to further investigate the relationship between estimated PMI and selected influencing factors, including correction factor, body weight, height, and age. Scatter plots are generated to visualise the distribution of the data and the general tendency of the relationships. Normality assessment indicated that the data did not satisfy the normality assumption. Therefore, Spearman rank correlation is applied to evaluate the strength and direction of monotonic associations between absolute error and the selected factors. The statistical significance of these associations is determined based on the corresponding p-values, ensuring a valid correlation analysis despite deviations from normal data distribution.

3. Result and Discussion

3.1 Error Behaviour of PMI Estimation Methods

The accuracy of the Newton cooling method and the Modified Henssge method is compared based on absolute error and MAE at two observation times: 12 PM (early post-mortem) and 8 PM (extended post-mortem). Both approaches had comparatively low error rates at 12 PM, with the Henssge technique exhibiting a lower MAE of 0.8070 hours as opposed to the Newton method's 0.9135 hours, indicating that the Henssge method was more accurate in the early post-mortem stage. At 8 PM, however, a notable difference in performance became apparent. The Henssge method had a significant increase in error as shown by a MAE of 3.60849 hours, compared to the Newton method which showed significantly improved consistency with an MAE of only 0.6423 hours. These empirical results suggested that, although the Newton method maintains its levels of performance during longer post-mortem periods, the Henssge methodology deviates further out of the optimal accuracy.

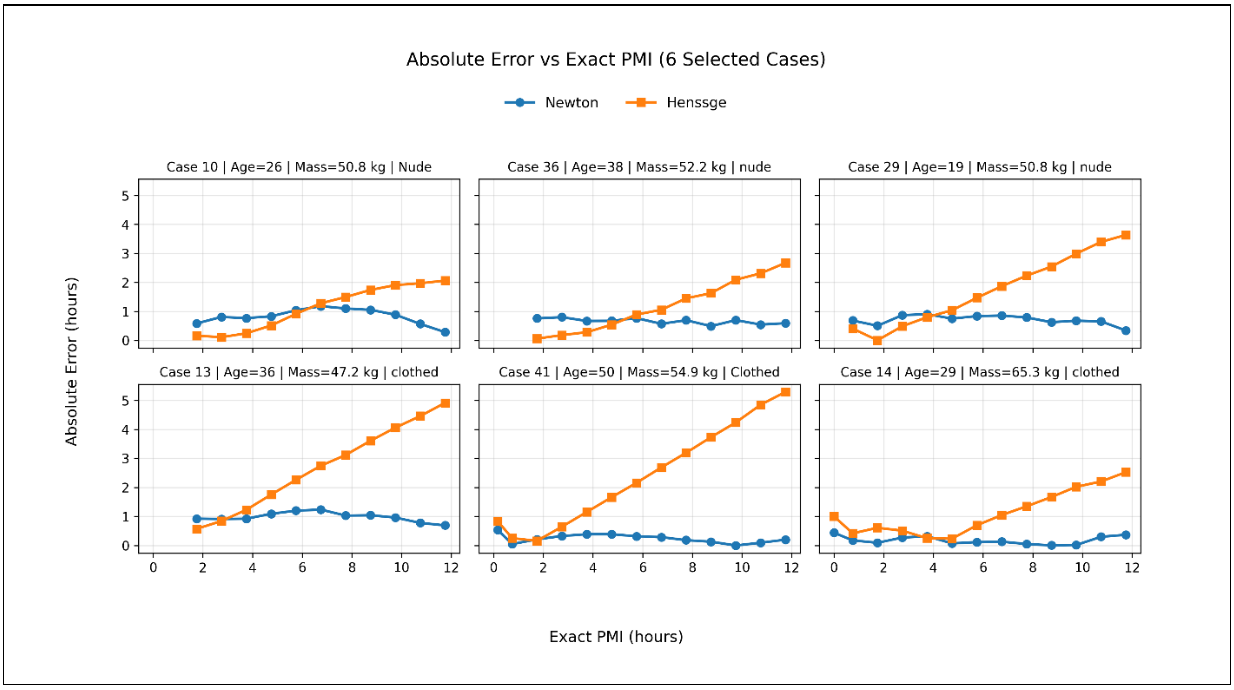

Fig. 1 *Absolute error vs Exact PMI graph*

The absolute error vs accurate PMI for a subset of cases with different body masses, ages, and body states is shown in Figure 1. According to the graph plot, the Henssge method's absolute inaccuracy rose dramatically between four and six hours after death and kept rising nearly consistently as the PMI grows. This demonstrates how the Henssge approach becomes less reliable over longer time periods, especially after eight hours post-mortem.

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However, the PMI may reach 12 hours but the error curve in the Newton method is flatter, with most of the oscillations falling below one hour. This finding supports the results of the MAE which showed that the Newton method has more advantages and reliability when dealing with long post-mortem times. These observations are in line with the forensic literature on algor mortis, assuming that estimations of temperature after 12 hours are unreliable due to a reduced temperature gradient between the body and the surrounding temperature [9]. Besides, practical evidence showed that the Henssge method achieved its highest accuracy during the first 10 hours after death. After this period, the reliability of the method decreased due to factors such as temperature equalisation and insulation effects from clothing. An increase in the magnitude of error is observed in the Henssge method after approximately 8 hours post-mortem.

3.2 Analysis of Factors Influencing Post-Mortem Interval: Correlation and Significance

Spearman's rho correlation analysis is used to examine the correlation between the correction factor, body weight, age, height, and the estimated PMI using Newton's Law of Cooling and the Henssge model at 12 p.m. and 8 p.m. The correlation coefficients and the corresponding p-values are shown in Fig. 2(a) and Fig. 2(b), while the correlation between the variables is shown in the scatter plot in Fig. 3(a) and Fig. 3(b).

Correlations

			correction factor	Weight	Age	Height
Spearman's rho	Newton's law of cooling PMI		-.067	.106	.238	.239
			.741	.598	.232	.230
			27	27	27	27
	Henssge model PMI		-.476	.064	.048	.115
			.012	.752	.812	.569
			27	27	27	27

Fig. 2(a) Spearman's Rho Correlation Between Post-Mortem Interval (PMI) and Selected Variables for Newton's Law of Cooling and Henssge Model at 12 p.m.

Correlations

			correction factor	Weight	Age	Height
Spearman's rho	Newton's law of cooling PMI		-.105	-.162	.132	.220
			.603	.420	.512	.269
			27	27	27	27
	Henssge Model PMI		-.676	-.465	-.165	.027
			.000	.015	.410	.893
			27	27	27	27

Fig. 2(b) Spearman's Rho Correlation Between Post-Mortem Interval (PMI) and Selected Variables for Newton's Law of Cooling and Henssge Model at 8 p.m.

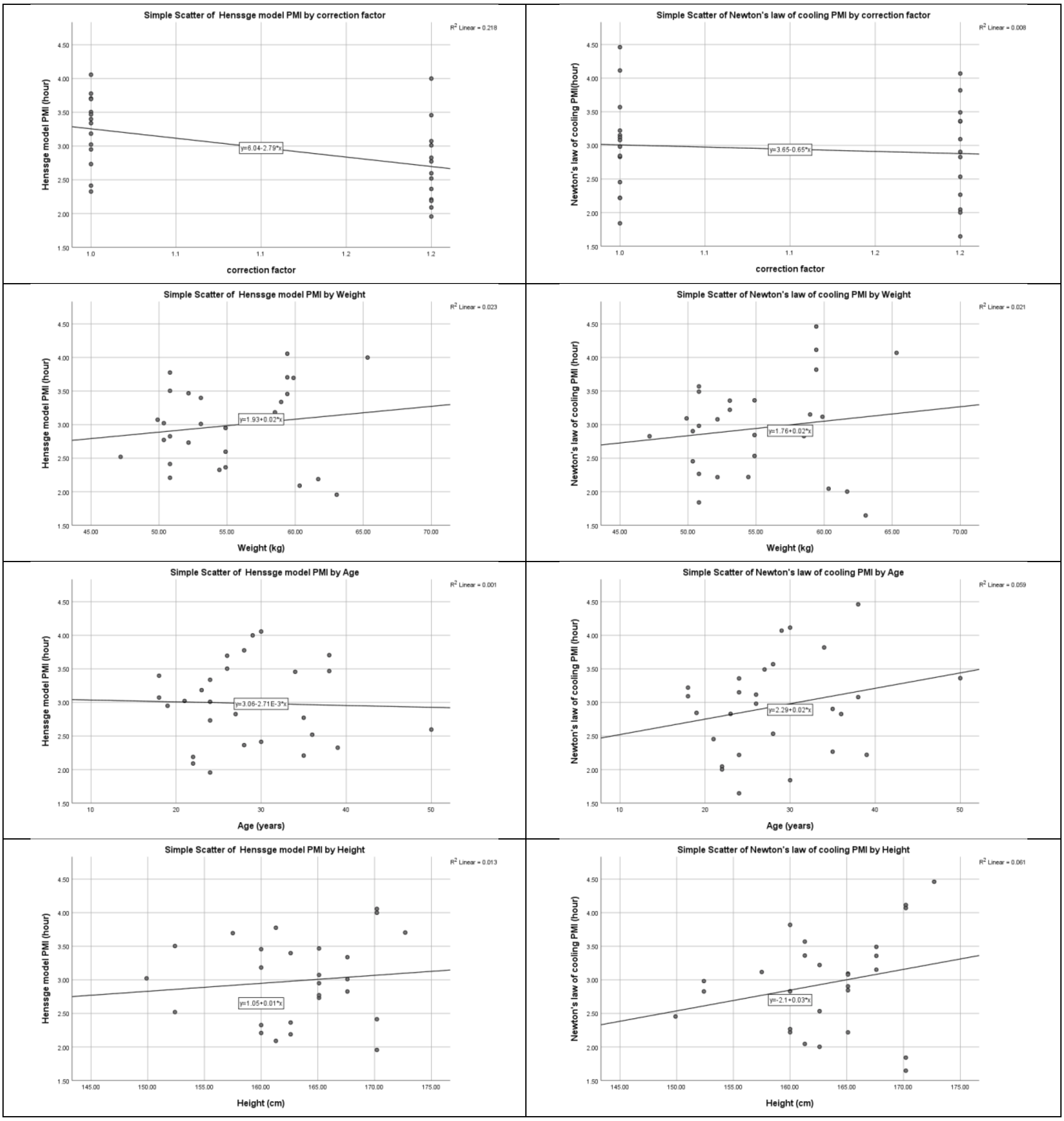

Fig. 3(a) Scatter Plots Showing the Relationship Between PMI and Selected Variables at 12 p.m.

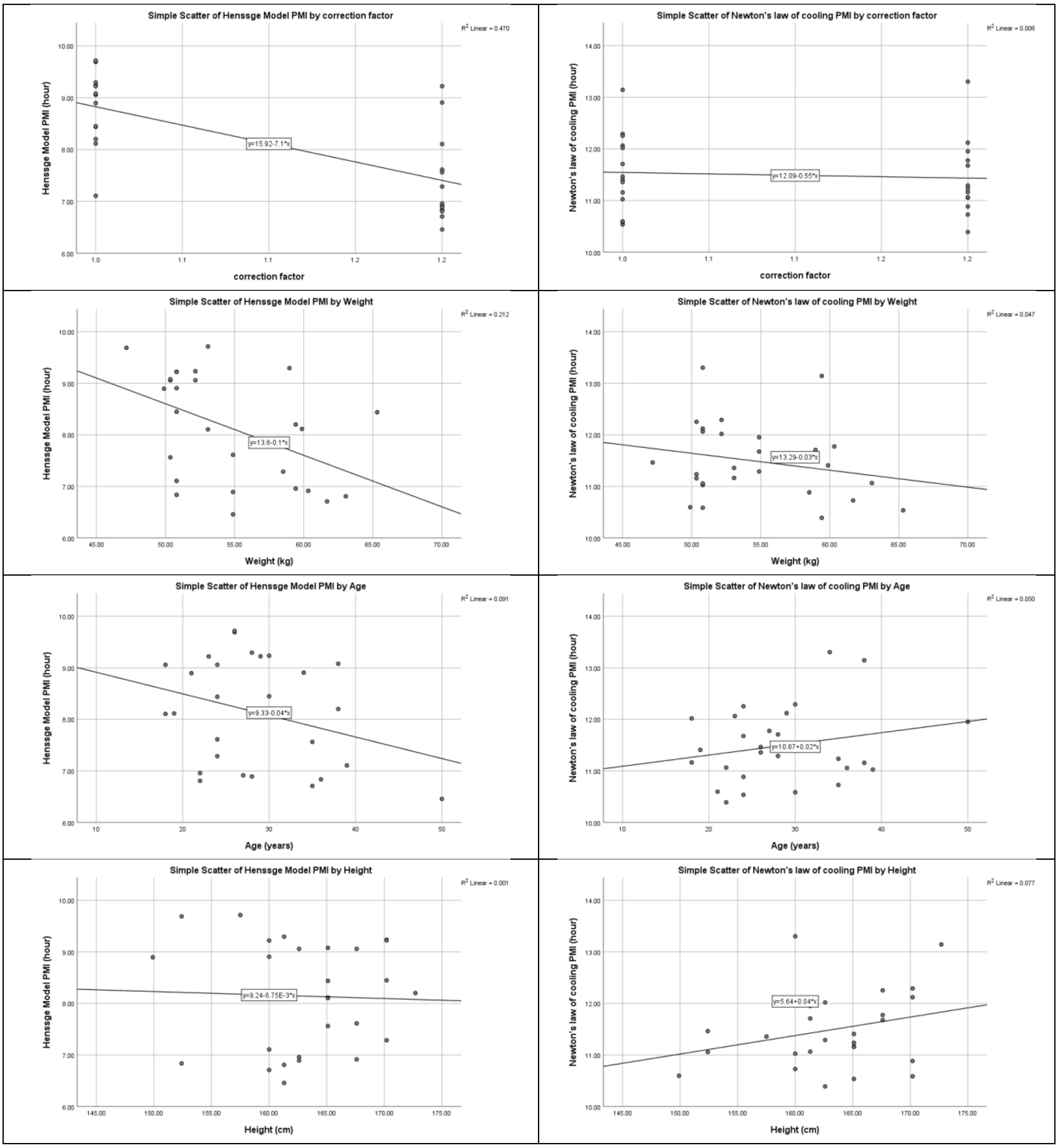

Fig. 3(b) Scatter Plots Showing the Relationship Between PMI and Selected Variables at 8 p.m.

For the estimated PMI using Newton's Law of Cooling at 12 pm, the correlation between the estimated PMI and the correction factor (ρ = -0.067), body weight (ρ = 0.106), age (ρ = 0.238), height (ρ = 0.239) was found to be statistically non-significant ($p > 0.05$).

For the estimated PMI using the Hensghe model at 12 pm, the correlation between the estimated PMI and the correction factor was found to be moderate and negative (ρ = -0.476, p = 0.012), while the correlation between the estimated PMI and body weight, age, height was found to be weak, as shown in the scatter plot.

At 8 pm, Newton's Law of Cooling again revealed weak and non-significant correlations with all variables, consistent with the general patterns observed in the scatter plots. On the other hand, PMI results obtained from the Henssge model revealed strong negative correlations with correction factor (ρ = -0.676, p = 0.00) and body weight found to be moderate negative (ρ = -0.465, p = 0.015).

Correlation coefficient interpretation was done according to Spearman's rho correlation coefficient, which is used to measure the strength of a relationship, where it is clear that Spearman's correlation coefficient measures both the strength and direction of a monotonic relationship, not linearity, where it is clear that it is not the value of the correlation coefficient itself, but its significance, which is of interest (Statstutor, Spearman's Rank Correlation). [10].

The weak levels of correlation revealed by Newton's Law of Cooling, supported by the results and the patterns observed in the scatter plots, suggest that this method is not sensitive to individual and environmental factors. This finding is consistent with the theory of algor mortis, which states that the post-mortem cooling process is a simple physical phenomenon and that the effect of physiological and environmental factors is not explicitly considered in the theory [11].

In contrast, the Henssge model revealed more meaningful and statistically significant results, especially in relation to the correction factor and body weight. These findings are consistent with the forensic literature that emphasizes the significance of insulation effects, body mass, and environmental conditions in estimating PMI [12]. The increasing trend of the results, especially at 8 pm, implies that the factors become more significant as the post-mortem cooling process continues.

The influence of body weight on the estimation of PMI was also supported by previous studies that considered temperature, body weight, and physiological factors in the estimation of PMI [13]. The lack of meaningful correlations with age and height implies that the factors have minimal influence compared to the correction factor and body weight.

Overall, the numerical and graphical results indicate that the model of Henssge is more sensitive to correction-related and anthropometric variables, as indicated by the patterns of correlation. However, it should be noted that the sensitivity to influencing factors should be distinguished from the accuracy of estimation, which will be analysed using the MAE method in the following section.

4. Conclusion

This study evaluated the accuracy and reliability of Newton cooling method and Henssge model of estimating PMI. The results revealed that the Henssge model proved to be slightly more accurate during the early post-mortem stage, but the Newton model is more stable and consistent in the long term. Despite this fact, the research has a number of limitations. First, it was based on the secondary data that was taken out of an already existing forensic database, thus restricting the researcher the possibility to regulate the environment. Besides, the assumption of a standard initial body temperature and the standardization of the time of death might not reflect real forensic situations. Possible nonlinear relationships among the variables could have also been concealed by the use of linear correlation methods. Also, it was only algor mortis that was analysed and no other post-mortem indicators were taken into account. Future research must also include more current and diverse forensic data that covers a more diverse set of variables, and must also incorporate the modern methods of data collection. Besides, the implementation of advanced computational models, such as machine learning, promises to explain non-linear, complicated correlations between determinants, thus strengthening the accuracy of PMI estimation models, and leveraging these developments in forensic settings.

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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 authors confirm contribution to the paper as follows: **study conception and design**: Nur Aina Umira Norahim, Norzuria Ibrahim; **data collection**: Nur Aina Umira Norahim; **analysis and interpretation of results** Nur Aina Umira Norahim, Norzuria Ibrahim; **draft manuscript preparation**: Nur Aina Umira Norahim, Norzuria Ibrahim. All authors reviewed the results and approved the final version of the manuscript.*

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