Stochastic Degradation Modeling of a Peristaltic Pump in a Biomedical Blood Autotransfusion System

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This study compares two stochastic models, Brownian Motion with Drift and the pure Wiener Process, applied to the degradation of a peristaltic pump used in a biomedical device. Failure was defined as the reduction of flow rate below a critical threshold required for safe operation. Simulations showed that the Wiener Process consistently produced higher time-to-failure (TTF) values across all scenarios, with larger differences under low and moderate variability (σ = 0.05 and σ = 0.3) and smaller differences under high variability (σ = 0.8). The observed effect results from the deterministic component in Brownian Motion with Drift, which accelerates average degradation, while the Wiener Process is driven solely by random fluctuations, allowing greater variability in failure time. Findings indicate that, in biomedical applications, selecting an appropriate degradation model is crucial for accurate lifetime predictions and predictive maintenance planning, particularly in low-variability environments. Future work should integrate stochastic degradation models with statistical monitoring techniques to improve early fault-detection accuracy and enhance the robustness of lifetime estimation under real operating conditions.
Keywords: Stochastic Models. Degradation. Peristaltic Pump. Predictive Maintenance. Wiener Process. Brownian Motion with Drift.

Autotransfusion devices play a crucial role in the global healthcare setting, primarily because they reduce patient blood loss and concentrate red blood cells for reinfusion, thereby minimizing the need for allogeneic blood transfusions [1]. The effective operation of these devices requires integrating multiple components, such as a centrifuge for blood separation and a peristaltic pump for fluid transfer in different directions, as in the case of the AutoLog system, according to the device's user manual. It is noteworthy that the primary requirements for autotransfusion devices are to prevent contamination of the patient's blood and to ensure precise control of the flow rate of the fluids involved [2].

Given these requirements, the peristaltic pump is well-regarded for meeting them, as it exhibits characteristics that ensure high reliability, such as the absence of direct contact between the pump mechanism and the system fluid, high flow rate accuracy, and ease of maintenance. These features demonstrate its effectiveness in the development of biomedical equipment [3].

Peristaltic pumps, also classified as infusion pumps, are essential for the operation of autotransfusion devices. In this regard, it is important to highlight the importance of maintaining these devices, as their failure may lead to severe patient complications, including venous spasms, pulmonary edema, and thrombophlebitis [4]. In this context, predictive maintenance is characterized by the continuous monitoring of critical operational parameters of equipment [5], providing essential data for decision-making aimed at preventing complete operational failure and thereby ensuring device reliability [6]. For this reason, condition-based maintenance is considered the most effective approach for peristaltic pumps [7].

In parallel with maintenance strategies, degradation models serve as a valuable tool for enabling more efficient asset management, contributing to both resource optimization and safety [8], given their capability to represent how

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a system deteriorates or evolves, allowing the prediction of failures and degradation [9]. This, in turn, can help reduce uncertainties in decision-making and future projections [10], as well as improve system reliability and durability [11].

It is possible to identify the Brownian motion with drift [12] and the Wiener process [13] in the context of degradation models. Brownian motion is characterized as a stochastic model that simulates the degradation of a system or variable over time, incorporating a directional trend [14]. In contrast, the Wiener process is a stochastic model that describes system degradation in a purely random manner over time [15]. Both models can be applied to the analysis of fluid flow in a peristaltic pump.

This study aims to develop, simulate, and compare the two presented stochastic models to predict the time-to-failure (TTF) of peristaltic pumps in autotransfusion devices, and to contribute to understanding the application of degradation models in the context of biomedical equipment.

Materials and Methods

The peristaltic pump is a mechanical device used in a wide variety of biomedical equipment, including autotransfusion systems, due to its ability to move fluids in a controlled manner while minimizing direct contact with moving parts, thus ensuring the integrity of the biological fluid. This study focuses on analyzing the gradual wear of the pump's mechanical components, which can reduce operational performance and lead to eventual failure. To model the pump's degradation process, two stochastic methods were compared: Brownian Motion with Drift, which incorporates a deterministic trend associated with the average wear rate, and the pure Wiener Process, which considers only the random component of the phenomenon, without a defined trend. This comparison aims to identify which approach more realistically represents the degradation evolution of the peristaltic pump.

The degradation model based on Brownian Motion with Drift describes the wear evolution as the sum of a deterministic component and a random term. In this way, the drift represents the average degradation rate over time, while the stochastic term models the inherent random fluctuations of the process, such as variations in friction or minor operational irregularities. The equation representing the wear X(t) is commonly expressed as follows [16]:

$$dX(t) = \mu\, dt + \sigma\, dW(t) \tag{1}$$

Where μ is the drift coefficient, representing the average wear rate, σ is the intensity of the stochastic variability, and W(t) is the standard Wiener process. The development of this equation allows modeling the accumulated wear over time [16]:

$$X(t) = X(0) + \mu(t) + \sigma W(t) \tag{2}$$

This model is widely used to represent the physical degradation of mechanical components, accounting for both the average failure trend and the random variations that can accelerate or delay the process.

The pure Wiener process describes degradation as an evolution of a purely random characteristic, devoid of any systematic trend. In this model, the wear is represented by the following equation [16]:

$$X(t) = X(0) + \sigma W(t) \tag{3}$$

In addition to stochastic models, to model the degradation of the peristaltic pump more realistically, it is necessary to consider deterministic effects associated with pressure loss and random noise. Zhai and colleagues (2024) [17] represent the pressure loss by a quadratic function of time, which expresses the continuously increasing wear related to prolonged operation, as shown below:

$$P(t) = \alpha t2 \tag{4}$$

For the simulation of the peristaltic pump, parameters were selected based on real data from interviews with a perfusionist and the client who requested the project, ensuring greater practical adherence to the peristaltic pump's operating conditions.

The pump flow rate under normal operating conditions is 600 mL/min, and this value was fixed in the developed model. In comparison, the equipment failure threshold was set at 480 ml/min, equivalent to 80% of the initial flow rate, which marks the point at which the equipment's performance is considered compromised. The time step was defined as 1 minute, a time resolution suitable for tracking the degradation evolution over the maximum simulated duration of 500 hours (30,000 minutes).

The intensity of the stochastic noise was simulated at three levels: 0.05, 0.3, and 0.8. This variation aimed to represent different operational magnitudes and mechanical imperfections inherent to the process. Table 1 presents the simulation parameters.

Table 1. Simulation parameters for peristaltic pump degradation modeling.

Parameter	Value(s)
Initial Flow ($q0$)	600 mL/min
Failure Threshold (L)	480 mL/min (80% of $q0$)
Time step (dt)	1 minute
Maximum time	500 hours
Noise intensity (σ)	0.05; 0.3; 0.8

The computational simulation was implemented in MATLAB to model the degradation of the peristaltic pump using two distinct stochastic models: Brownian Motion with Drift and the pure Wiener Process. For each model, multiple individual degradation trajectories over time were generated, incorporating stochastic noise and deterministic components. The simulation progressed iteratively until the pump flow reached the established failure threshold or the maximum operating time was reached. During the process, the time-to-failure (TTF) was recorded for each simulation, enabling quantitative analysis of the useful life and comparison of the two models under different variability conditions.

Results

This section presents the results of simulations evaluating the time-to-failure (TTF) of a peristaltic pump used in autologous blood transfusion equipment, accounting for different levels of uncertainty in the degradation process. Two stochastic models were analyzed: Brownian Motion with Drift and the pure Wiener Process. The models were applied to three distinct scenarios of stochastic variability (σ = 0.05, 0.3, and 0.8). The use of these models is relevant for medical applications in which the continuous and safe operation of the pump is highly critical for the integrity of the transfusion procedure and the patient, enabling the anticipation of interventions and reducing the risk of unexpected failures.

In the scenario with σ = 0.05, characterized by low variability, the estimated TTF was 11,070.00 minutes (184.50 h) for the Brownian Motion with Drift model and 15,174.00 minutes (252.45 h) for the pure Wiener Process. At this level of uncertainty, it is observed that the pure Wiener model yielded a time-to-failure greater than that obtained with the Brownian Motion with Drift. Figure 1 presents the simulation results for σ = 0.05.

In the scenario with σ = 0.3, representing moderate process variability, the TTF was 8,786.00 minutes (146.43 h) for the Brownian Motion with Drift model and 12,744.00 minutes (212.40 h) for the Wiener process. As in the previous scenario, the Wiener process showed higher values compared to the Brownian Motion with Drift. Figure 2 presents the simulation results for σ = 0.3.

In the high-variability scenario, modeled with σ = 0.8, the estimated TTF was 6,842.00 minutes (114.03 h) for the Brownian Motion with Drift model and 8,002.00 minutes (133.37 h) for the Wiener process. In this case, the TTF difference between the two models decreased. Figure 3 presents the simulation for the σ = 0.8 scenario.

Figure 1. Comparison between the two stochastic models for σ = 0,05.

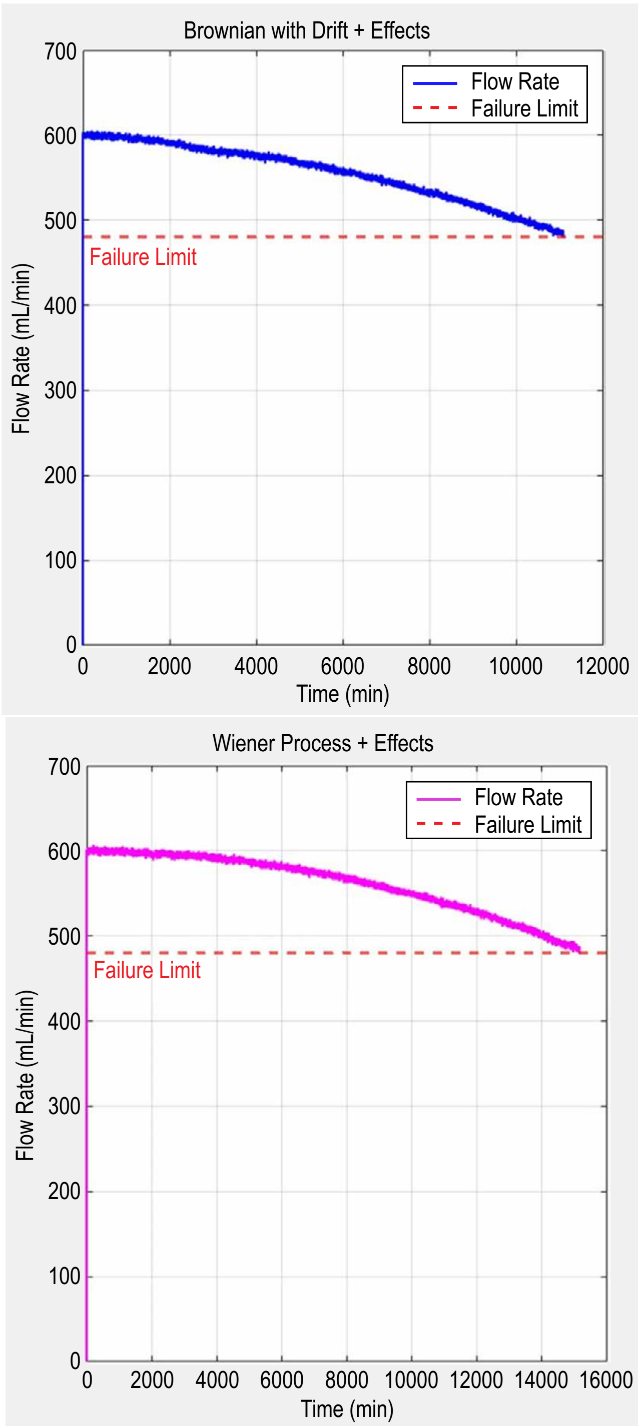


Figure 2. Comparison between the two stochastic models for σ = 0,3.

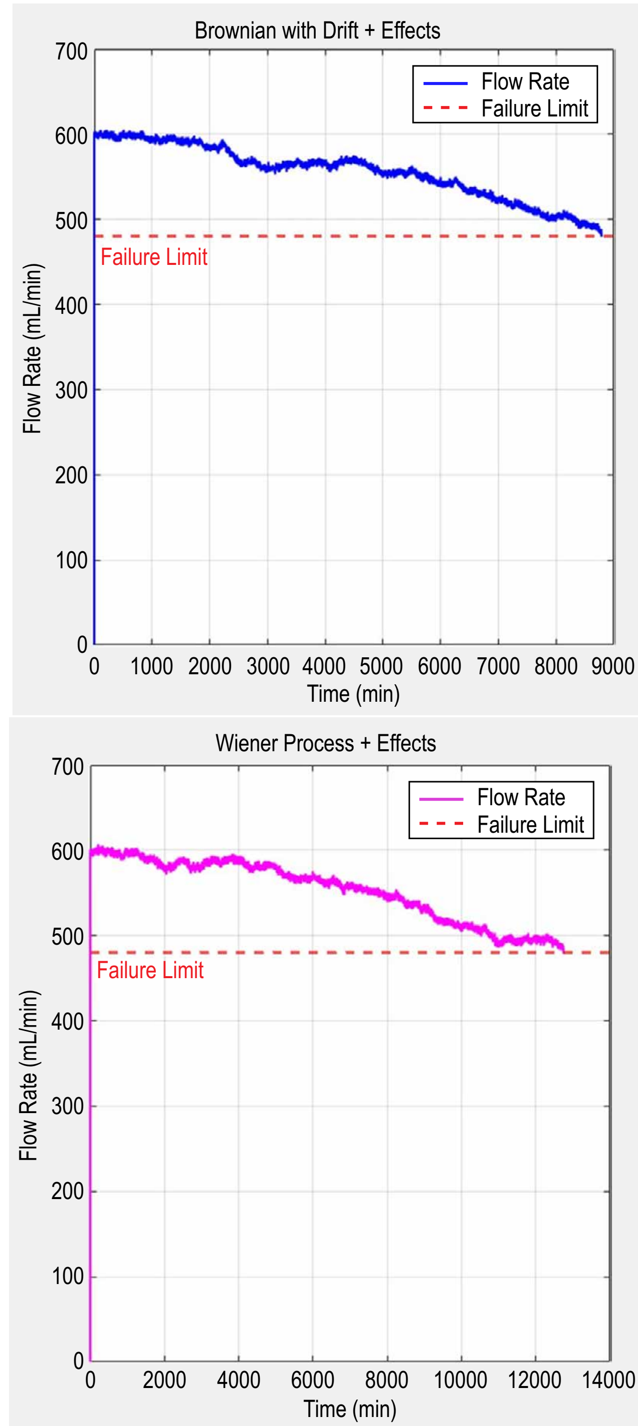
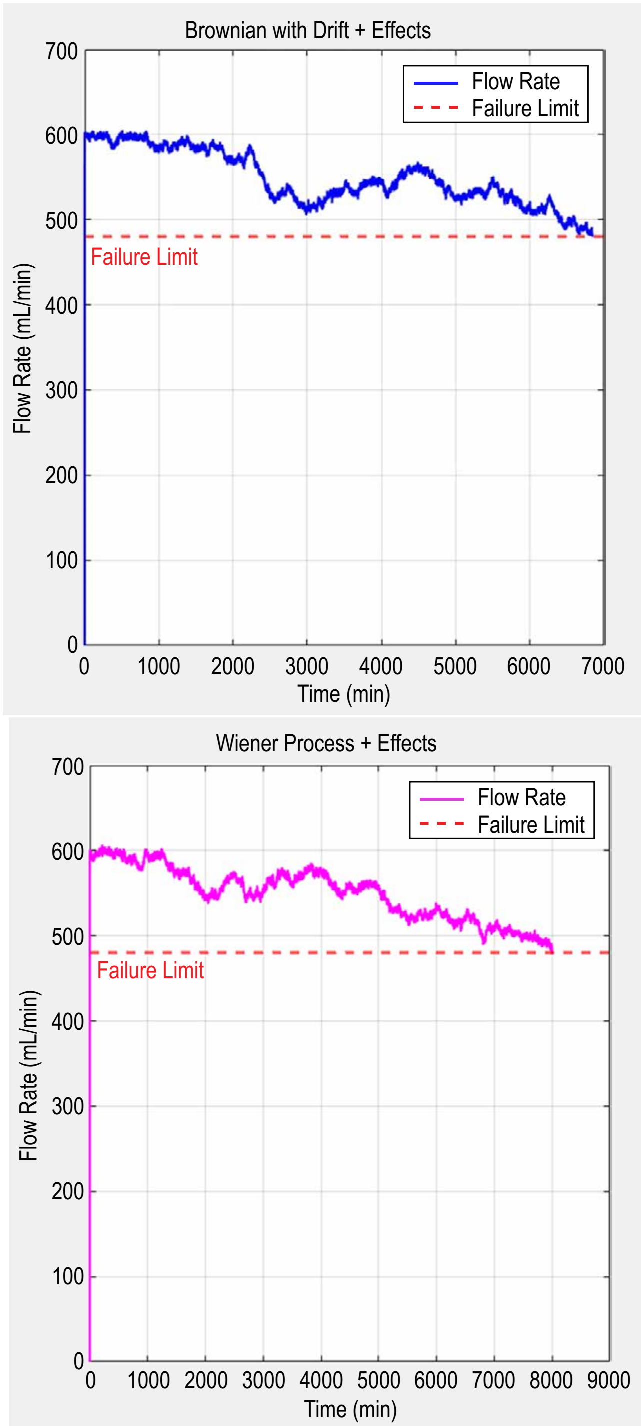


Figure 3. Comparison between the two stochastic models for σ = 0,8.



Discussion

The comparative analysis between the stochastic models of Brownian Motion with Drift and the pure Wiener Process reveals a consistent pattern: across all simulated scenarios, the Wiener Process exhibited higher time-to-failure (TTF) values than the Brownian Motion with Drift model. This difference is more pronounced in low- and moderate-variability scenarios ($\sigma = 0.05$ and 0.3) and decreases as process variability increases ($\sigma = 0.8$).

The study was conducted to assess the degradation of a peristaltic pump used in a biomedical device, where failure is defined as a reduction in flow rate below a critical threshold required for the safe and effective operation of the system. In this context, understanding the influence of the chosen stochastic model is crucial for accurately estimating the component's lifetime and for planning predictive maintenance actions.

The intrinsic characteristics of each model can explain the observed behavior. In Brownian Motion with Drift, the deterministic term (drift) tends to guide the degradation trajectory toward the failure threshold more consistently, accelerating the average wear rate. In contrast, in the pure Wiener Process, evolution is governed solely by the stochastic term, leading to larger cant oscillations around the mandalich in some c, delaying the attainment of the failure threshold.

In the high variability scenario ($\sigma = 0.8$), the TTF difference between the models is considerably reduced. This occurs because increasing the σ parameter amplifies the random effect in both models, making the drift's influence relatively less dominant and bringing the simulated trajectories closer together. In this regime, the impact of random fluctuations prevails over the deterministic component, leading to more irregular, less predictable degradation trajectories.

From a practical perspective, these results indicate that for peristaltic pumps in biomedical applications, the choice of stochastic model can significantly affect lifetime predictions, particularly in processes with low or moderate variability. Under high-variability conditions, the influence of the chosen model decreases, though it may still be relevant depending on the system's reliability requirements.

Conclusion

The comparative study between Brownian Motion with Drift and the pure Wiener Process, applied to the degradation of a peristaltic pump used in a biomedical device, demonstrated that the choice of stochastic model directly affects the estimation of time-to-failure (TTF). In all scenarios analyzed, the Wiener Process yielded higher TTF values, with the difference more pronounced under low and moderate variability conditions and less pronounced in high-variability scenarios.

The findings suggest that, for biomedical applications where reliability and operational safety are critical, selecting an appropriate degradation model is essential for accurate lifetime predictions and effective predictive maintenance planning. Furthermore, the influence of the chosen model is more relevant in processes with lower variability. In contrast, in highly variable environments, the random component tends to dominate, reducing the differences between the approaches.

As a recommendation for future work, it is suggested to explore hybrid systems that combine stochastic degradation models with statistical monitoring techniques, such as control charts, to enhance early fault-detection accuracy and improve the robustness of lifetime estimation in real operating conditions.

References

1. Conceição MJ. Transfusão sanguínea em crianças e os métodos para evitá-la: uma reavaliação. Rev Bras Anestesiol. 2004;54(2):276-82. Disponível em: https://www.scielo.br/j/rba/a/YXYJ9fR84HSQ5SsnTZFFBgc/.
2. Mello MAA. Avaliação da recuperação de sangue intra e pós-operatória em pacientes submetidos à cirurgia cardíaca com circulação extracorpórea [dissertação]. Campo Grande: Universidade Federal de Mato Grosso do Sul; 2024.
3. Santos AR, Neilson MLH. Bomba peristáltica de duto flexível: reprojeto e melhorias [trabalho de conclusão de curso]. São Paulo: Universidade de São Paulo; 2008.
4. Silva MS, et al. Reliability analysis of hospital infusion pumps: a case study. Biomed Eng Online. 2025;24:55. Disponível em: https://link.springer.com/article/10.1186/s12938-025-01389-2.
5. Zhao Y, et al. Condition-based maintenance for a multi-component system subject to heterogeneous failure dependences. Reliab Eng Syst Saf. 2023;239. Disponível em: https://www.sciencedirect.com/science/article/pii/S0951832023003976.
6. Kardec A, Nascif J. Manutenção: função estratégica. 3. ed. Rio de Janeiro: Qualitymark; 2009.
7. Zamzam AH, Hasikin K, Wahab AKA. Integrated failure analysis using machine learning predictive system for smart management of medical equipment maintenance. Eng Appl Artif Intell. 2023;125. Disponível em: https://www.sciencedirect.com/science/article/pii/S0952197623008990.
8. Park C, Padgett WJ. Stochastic degradation models with several accelerating variables. IEEE Trans Reliab. 2006;55(2):379-90. doi:10.1109/TR.2006.874937.
9. Cai Y, Teunter RH, de Jonge B. A data-driven approach for condition-based maintenance optimization. Eur J Oper Res. 2023;311:730-8. doi:10.1016/j.ejor.2023.05.002.
10. Marotta RD. Modelagem da degradação da superestrutura ferroviária e otimização na alocação de recursos para manutenção [trabalho de conclusão de curso]. Juiz de Fora: Universidade Federal de Juiz de Fora; 2016.
11. Zhang X, et al. Multiple-failure mode division and condition-based maintenance decision making for systems with multi-indicator performance degradation. Comput Ind Eng. 2024;191:110118. Disponível em: https://www.sciencedirect.com/science/article/pii/S0360835224002390.
12. Kadloor S, Adve RS, Eckford AW. Molecular communication using Brownian motion with drift. IEEE Trans Nanobioscience. 2012;11(2):89-99.
13. Zhang Z, et al. Degradation data analysis and remaining useful life estimation: a review on Wiener-process-based methods. Eur J Oper Res. 2018;271(3):775-96.
14. Arias E, Morett G. Confecção de um modelo mecânico análogo para o estudo do movimento browniano e da difusão molecular. Rev Bras Ens Fis. 2023;45:e20230008.
15. Oliveira SC. Modelagem baseada em equações diferenciais estocásticas não-lineares para dinâmica de preços [tese]. Belo Horizonte: CEFET-MG; 2023.
16. Whitmore GA, Schenkelberg F. Modelling accelerated degradation data using Wiener diffusion with a time scale transformation. Lifetime Data Anal. 1997;3(1):27-45.
17. Zhai Q, Li Y, Chen P. Modeling product degradation with heterogeneity: a general random-effects Wiener process approach. IISE Trans. 2024:1-14.