https://doi.org/10.47993/gmb.v48i1.959

An analysis of the effect of syringe barrel volume on mechanical failure during injection

Un análisis del efecto del volumen del cuerpo de la jeringa sobre la falla mecánica durante la inyección

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Abstract

Background: syringes are critical medical devices whose mechanical integrity is essential to ensure safety during injections. The cylinder volume can influence their mechanical performance.
Objective: this study investigates how cylinder volume affects the mechanical integrity of syringes by analyzing von Mises stress, buckling risk, and overall safety during injection.
Methods: autodesk Inventor 2021 and Ansys 2019 R2 were used to analyze syringes with volumes of 1 ml, 3 ml, 5 ml, and 10 ml. Von Mises stress and buckling susceptibility were evaluated during simulated injections.
Results: smaller syringes showed higher stress levels: 14.030 MPa for the 1 ml syringe, 10.532 MPa for the 3 ml, and 7.0150 MPa for the 5 ml and 10 ml. The 5 ml syringe was the most susceptible to buckling, with a critical pressure of -0.1757 MPa. Despite this, all designs are safe under normal operating conditions.
Conclusions: cylinder volume affects mechanical performance, but with proper design, even smaller syringes can remain safe, enhancing the reliability of medical treatments.
Keywords: barrel volume, buckling susceptibility, syringe design optimization, syringe mechanical integrity, von mises stress.

Resumen

Antecedentes: las jeringas son dispositivos médicos críticos cuya integridad mecánica es esencial para garantizar su seguridad en las inyecciones. El volumen del cilindro puede influir en su rendimiento mecánico.
Objetivo: este estudio investiga cómo el volumen del cilindro afecta la integridad mecánica de las jeringas, analizando la tensión de von Mises, el riesgo de pandeo y la seguridad general durante la inyección.
Métodos: se utilizaron Autodesk Inventor 2021 y Ansys 2019 R2 para analizar jeringas de 1 ml, 3 ml, 5 ml y 10 ml. Se evaluaron las tensiones de von Mises y la susceptibilidad al pandeo durante inyecciones simuladas.
Resultados: las jeringas más pequeñas presentaron mayores esfuerzos: 14,030 MPa para la de 1 ml, 10,532 MPa para la de 3 ml y 7,0150 MPa para las de 5 ml y 10 ml. La jeringa de 5 ml fue la más susceptible al pandeo, con una presión crítica de -0,1757 MPa. A pesar de ello, todas son seguras bajo condiciones normales.
Conclusiones: el volumen del cilindro afecta el rendimiento mecánico, pero con un buen diseño, incluso las jeringas pequeñas pueden ser seguras, mejorando la fiabilidad de los tratamientos médicos.
Palabras claves: volumen del cilindro, susceptibilidad al pandeo, optimización del diseño de la jeringa, integridad mecánica de la jeringa, tensión de von Mises.

Recibido el
24 de abril de 2024
Aceptado
20 de febrero de 2025
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DOI:
https://doi.org/10.47993/gmb.v48i1.959

Syringes are essential medical devices used to inject liquids into patients. The primary components of a syringe include the plunger, barrel, and needle[1,2]. Among these, the barrel volume is a critical factor that can influence the mechanical integrity and reliability of syringes during injections. Investigating the effect of barrel volume on mechanical failure is urgent to ensure safe and effective medical treatments[3–5].

Recent studies have highlighted that varying barrel volumes can lead to different stress distributions within the syringe structure. For instance, larger barrel volumes have been shown to increase the Von Mises stress, which is a key indicator of the material's ability to withstand mechanical loads without failing[3]. This increased stress is critical because it suggests a higher likelihood of mechanical failure under typical usage conditions[6,7].

Furthermore, buckling tests have revealed that syringes with larger barrel volumes are more susceptible to buckling under compressive forces. Buckling can lead to catastrophic mechanical failures, especially during high-pressure injections. The findings from buckling analysis underscore the need for careful consideration of barrel volume in syringe design to prevent such failures and ensure patient safety[1,2].

These mechanical failures are often highlighted through detailed analyses of Von Mises stress distribution and buckling tests. For example, larger syringes have demonstrated higher stress concentrations under operational conditions, leading to higher risks of buckling[8,9]. Additionally, the variations in syringe barrel volume significantly impact the force required to operate the plunger, as evidenced by multiple studies [10].

This article is structured into four sections. Section 1 presents the introduction and background of the study. Section 2 discusses the materials and research methodology, including the specific tests and analyses conducted. Section 3 elaborates on the results and discussions based on the findings. Finally, Section 4 provides the conclusions drawn from this research.

Material and methods

This research comprised several main steps. The first step involved creating 3D geometries of polypropylene syringes using Autodesk Inventor 2021. In this study, the independent variable was the barrel volume, which was set at 1 ml, 3 ml, 5 ml, and 10 ml. The shape and design of the syringe are shown in Figure 1. Accordingly, the 3D geometries drawn represented syringes with these specified volumes. Upon completion of the 3D geometries, the second step was to perform injection simulations using Ansys 2019 R2 to obtain the distribution of von Mises stress. The simulations were conducted by applying pressure to the areas of the syringe that experience stress during the injection process. The pressures applied were 3.86106 MPa for 1 ml, 1.95122 MPa for 3 ml, 0.82047 MPa for 5 ml, and 0.56537 MPa for 10 ml [11].

To confirm the validity of the simulation results, stress validation was performed by comparing the von Mises stress values on the shell of the simulation results with those calculated using an equation. Equation 1 was used to determine the stress between the outer and inner diameters[12]. Figure 2 illustrates the position of the points used for von Mises validation using Equation 1. The von Mises stress in the middle of the outer and inner diameters was compared with the equation results for shell stress. For the simulation to be considered valid, the results needed to be within a 5% difference[13]. was used to determine the stress between the outer and inner diameters[12]. Figure 2. shows the position of the point used for von Mises validation using Equation 1.

$$\sigma_{vm} = \sqrt{\sigma_H^{\ 2} - \sigma_H^{\ 2}.\sigma_L^{\ 2} + \sigma_L^{\ 2}} \quad (1)$$

Where:
σ_{vm} = shell stress (MPa)
σ_H = hoop stress (MPa)
σ_L = longitudinal stress (MPa)

$$(2) \quad \sigma_L = \frac{Pd}{4t} \qquad \sigma_H = \frac{Pd}{2t} \quad (3)$$

P = internal pressure (MPa)
d = shell diameter (m)
t = shell thickness (m)

Equation (2) was used to compute longitudinal stress, while equation (3) was used to calculate hoop stress.

After ensuring the validity of the simulation results, the next step was to analyse the von Mises stress distribution and load multiplier from the buckling simulation results. This analysis aimed to assess the likelihood of mechanical failure during the injection process.

Figura 1. The syringe's design.

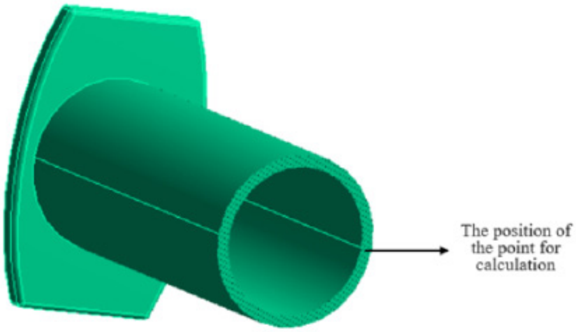

Figura 2. The position of the point for calculation

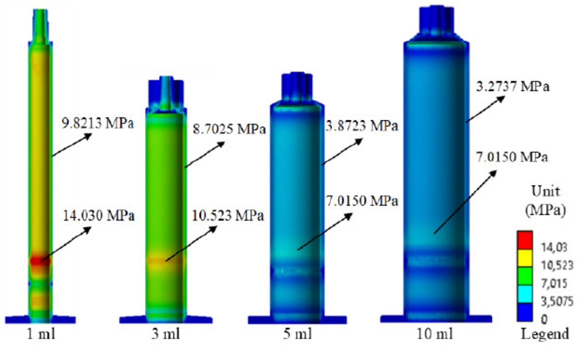

Figura 3. Von Mises stress distribution on the inner diameter of the syringe barrel

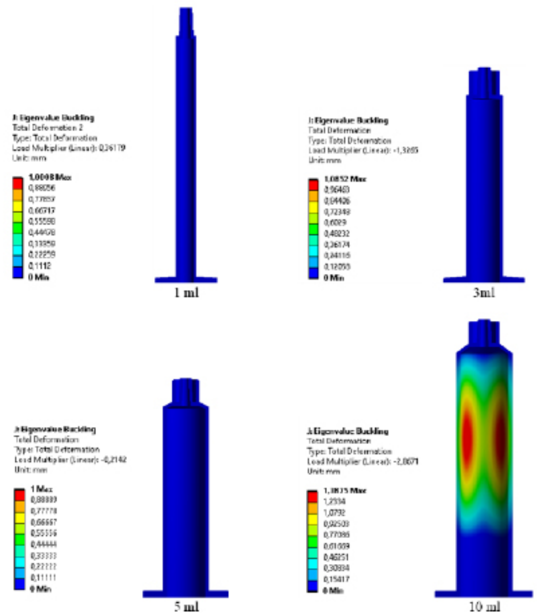

Figura 4. Total deformation on the inner diameter of the syringe barrel when buckling and load multiplier.

Result and Discussion

Von Mises Stress Distribution

During the injection process, force was intentionally applied to the inner diameter of the barrel, creating internal pressure and consequently inducing von Mises stress within the barrel walls. The von Mises stress, which measures the material's distortion energy under load, serves as an indicator of the barrel's strength and resilience. To validate the simulation's accuracy and reliability, the von Mises stress values derived from the simulation were compared with those obtained through manual calculations. This comparative analysis is summarized in Equation 1 and detailed in Table 1. The stress values were measured at the midpoints of the barrel's inner and outer diameters.

Table 1 presents a comparative analysis of stress results obtained through simulation and manual calculations, demonstrating that the error margin remains below 5%. This indicates that the simulation results are valid and reliable.

Figure 3 illustrates the von Mises stress distribution within the internal barrel, which is predominantly impacted by the pressure during the injection process. The applied load in the simulation induced von Mises stress within the geometrical structure of the syringe design, with the internal barrel wall experiencing the most significant stress impact.

The von Mises stress distribution which is shown in Figure 3 is a critical parameter in the analysis of material strength, particularly in evaluating the safety of products like syringes. According to the stress distribution results, it is evident that as the barrel volume of the syringe increases, the likelihood of failure decreases. This reduction in failure risk is attributed to the decreasing von Mises stress experienced during the injection process with larger barrel volumes. Generally, this indicates that syringe designs with larger barrel volumes offer an advantage in terms of reduced risk of material failure[14].

Moreover, despite the variations in barrel volume, all four types of syringes examined in this study are confirmed to be safe from fracture failure during injection use. This safety assurance is due to the fact that the maximum von Mises stress occurring in all syringe types is significantly below the yield strength of polypropylene, which is 28.06 MPa. In other words, the stresses encountered by the syringes do not approach the stress levels that could cause permanent deformation or fracture of the material[15].

The von Mises stress distribution presented in Figure 3 also provides valuable information that can be used to calculate the safety factor of these syringe designs. The safety factor is a measure used to determine the robustness of a design against material failure. By knowing the maximum von Mises stress and comparing it to the material's yield strength, the safety factor

Table 1. Stress comparison between simulation and calculation

Volume barrel (ml)	Simulation (MPa)	Calculation (MPa)	Error (%)
1	9,8213	9,82201	0,0
3	8,7025	8,7690	0,8
5	3,8723	3,9622	2,3
10	3,2737	3,2886	0,5

Table 2. Design safety factor of syringe

Volume barrel (ml)	Maximum von Mises stress (MPa)	Design safety factor
1	14,030	2,0
3	10,523	2,5
5	7,0150	4,0
10	7,0150	4,0

Table 3. Load multiplier and critical pressure when buckling occurs.

Volume barrel (ml)	Applied pressure (MPa)	Load multiplier	Critical pressure (MPa)
1	3,86106	-0,3618	-1,3969
3	1,95122	-1,3265	-2,5883
5	0,82047	-0,2142	-0,1757
10	0,56537	-2,8671	-1,6210

can be calculated, indicating the margin of safety within the design[16].

The use of polypropylene as the syringe material has proven to be effective given its mechanical properties, which are adequate to withstand the stresses during the injection process without reaching failure points. This supports the conclusion that syringe designs using this material, with varying barrel volumes, remain within safe limits for clinical use[17]. A comprehensive evaluation of the stress distribution provides a robust basis for ensuring the safety and reliability of syringe products in everyday medical applications[18].

Overall, the analysis of von Mises stress distribution and the calculation of the safety factor provide important insights for the development and testing of syringe designs. These findings not only ensure that the product is safe for use but also offer guidance for future design improvements to optimize the performance and safety of medical devices. As technology advances and new materials are developed, such analytical methods will continue to be integral in the design process of innovative and safe medical products[19]. The design safety factor is essential for evaluating the structural integrity of medical devices like syringes. It is calculated by comparing the maximum von Mises stress to the material's yield strength. Table 2 provides the design safety factor for syringes, classified by barrel volume.

The von Mises stress distribution results, as detailed in Table 2, were evaluated against the allowable stress to ascertain the safety factor of the design. The analysis revealed that only the 1 ml barrel exhibited an appropriate wall thickness, corresponding to a design safety factor of 2.0. Conversely, the other designs demonstrated safety factors that exceeded this recommended value, thus categorizing them as overdesigned.

A design safety factor of 2.0 is typically recommended for products subjected to dynamic loading conditions, especially when there is moderate confidence in the design data and the materials employed are ductile[20]. Overdesign, while ensuring higher safety margins, often results in material wastage, increased production costs, and inefficiencies[21]. In the context of sustainable engineering and cost-effective manufacturing, it is crucial to strike a balance between safety and material usage to avoid unnecessary expenditure and resource depletion. This study highlights the need for optimizing design parameters to achieve both safety and economic efficiency[22].

Buckling Testing

The results of buckling tests on a syringe are used to analyze the potential for buckling during the injection process. The simulation results for total deformation during buckling and load multiplier are presented in Figure 4.

Besides the distribution of total deformation during buckling, the buckling testing result also provides the load multiplier. The load multiplier is used to calculate the critical pressure, or the pressure when the buckling occurs. The critical pressure when buckling failure is the product of the multiplying load multiplier by the applied pressure[23]. The results of these calculations are presented in Table 3.

Table 3 indicates that all types of syringes are safe from buckling failure during the injection process. This is evidenced by the critical pressure values being negative, while the applied pressure during injection is positive. Previous research has shown that medical syringes are designed with various mechanisms to withstand internal pressure and prevent mechanical failures, including buckling. For instance, Riley and Carvalho (2007) confirmed that the spring-loaded syringe provides a consistent and objective endpoint for epidural space identification, making it a valuable tool in various clinical scenarios[24].

However, the results in Table 3 also indicate that syringes may experience buckling failure when subjected to vacuum pressure from within the barrel. Research on failure mode and effects analysis (FMEA) for medical devices has indicated that negative pressure can cause various structural issues in syringes[25].

Among the different syringes tested, the 5 ml syringe exhibited the highest likelihood of buckling, as it can only withstand a force of -0.1757 MPa. This finding aligns with previous studies showing that larger volume medical devices tend to be more vulnerable to internal negative pressure[26]. Conversely, the 3 ml syringe demonstrated the best resistance to buckling failure, capable of withstanding pressures up to -2.5883 MPa. This suggests that the size and design of syringes significantly affect their structural integrity under internal pressure.

Furthermore, the pressure generated by syringes varies significantly with size, which influences their performance in high-pressure applications such as hydro dissection and injection of dense connective tissue lesions. Smaller syringes have been found to generate significantly higher pressures than larger syringes, making them more effective for such procedures[11].

Additionally, safety syringes with various mechanisms to prevent needlestick injuries have been evaluated in clinical settings. Studies have shown that mechanical safety syringes and retractable syringes function well across various medical procedures, providing additional safety and reliability[27].

In conclusion, this study confirms that all types of syringes tested are safe from buckling failure during standard injection processes. However, the potential for failure exists under conditions of vacuum pressure, with the 5 ml syringe being the most susceptible and the 3 ml syringe being the most resilient. These findings are crucial for the design and usage considerations of syringes in medical practice to mitigate the risk of mechanical failure.

Conclusion

The analysis of von Mises stress distribution in syringe barrels during the injection process reveals that larger barrel volumes reduce the likelihood of material failure, indicating enhanced safety. The simulation results, validated by manual calculations, showed an error margin below 5%, confirming their reliability.

All tested syringes exhibited maximum von Mises stress levels well below the yield strength of polypropylene, ensuring safety from fracture failure. The design safety factor, which compares the maximum stress to the material's yield strength, indicated that while the 1 ml syringe had a safety factor of 2.0, other syringes were overdesigned, suggesting room for material optimization.

Buckling tests showed that syringes are safe from buckling under positive pressure but may fail under vacuum pressure. The 5 ml syringe was the most susceptible, while the 3 ml syringe was the most resilient.

Overall, the study confirms the safety and reliability of syringe designs, with polypropylene proving effective for withstanding injection stresses. The findings guide future syringe design improvements to optimize performance, safety, and material efficiency.

Conflict of Interest

The authors declare no conflict of interests.

Acknowledgements

The authors express their gratitude to the team members of the Centre for Sustainable and Smart Manufacturing (CSSM) laboratory for their invaluable knowledge sharing throughout the project. Additionally, the authors acknowledge Universitas Muhammadiyah Yogyakarta (UMY) for providing funding support for this research.

Acknowledgment

The authors would like to express their gratitude to CSSM Universiti Malaya and LRI Universitas Muhammadiyah Yogyakarta for providing the laboratory that allowed the research to proceed successfully.

Financing

The study was conducted independently, without any external funding or financial support.

Abbreviations

ml= milliliter, MPa= Mega Pascal, 3D= three dimension, %= percentage, = shell stress, = hoop stress, = longitudinal stress (MPa), = internal pressure, = shell diameter, = shell thickness

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