Analysis of bone cement distribution in vertebrae using pedicle screws with and without fenestrations

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ABSTRACT

With the increase in the life expectancy of the population, there are more and more health complications related to aging, such as osteoporosis. Among the complications resulting from osteoporosis, spinal fractures stand out. In some cases, pedicle screws are used to stabilize the spine. However, when screws are inserted into bone weakened due to osteoporosis, proper fixation of the screw may not occur. To reduce this problem, bone cement is injected into the vertebral body as a way to ensure better stabilization of the screws. One of the main complications of this procedure is related to the leakage of cement out of the vertebral body, causing several problems that affect health. The risks of cement leakage could be reduced by using Computational Fluid Dynamics (CFD) to analyze the distribution of bone cement in the vertebra. Thus, the objective of this research is to evaluate, by means of CFD, the fluid dynamic behavior of PMMA-based bone cement injection into vertebrae through pedicle screws with and without fenestrations. To study the cement flow inside the vertebra, a commercial software was used . The factors influencing the distribution of bone cement were evaluated and compared with results reported in the literature, showing good agreement with each other. The numerical results indicate that the use of fenestrated pedicle screws can improve screw stability and reduce the risk of bone cement leakage.

Keywords: Computational Fluid Dynamics, Osteoporosis, Vertebral fracture, Fenestrated screw.

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INTRODUCTION

With the increase in the life expectancy of the population and high rates of traffic accidents, falls, among others, there are more and more health problems related to the spine, such as fractures in the spine, and in most cases they occur in the older population and those suffering from osteoporosis. This pathology is characterized by a decrease in Bone Mineral Density (BMD), that is, the bone becomes weaker, becoming more susceptible to osteoporotic fractures of vertebral bodies that deforms the spine causing back pain, loss of ability to perform activities of daily living and, consequently, decreased quality of life.

Compression fractures of the vertebral body are one of the most frequent complications of osteoporosis. In cases where there is a need for surgical intervention for the treatment of these fractures, pedicle instrumentation is used to stabilize the spine by means of pedicle screws, which have been increasingly used, since they provide greater potential for correction of spinal deformities (MARCH, 2008).

However, when pedicle screws are inserted into the bone with reduced BMD, poor fixation can occur as low BMD causes a faulty screwed joint (ELDER *et al*., 2015; FU *et al*., 2017). Thus, since the force of pullout or detachment of the pedicle screw depends on the density of the bone, patients with osteoporosis are more susceptible to screw fixation failures and breakage (HICKERSON *et al*., 2013).

In order to reduce the problems in the treatment of patients with spinal fractures associated with osteoporosis, a procedure called vertebroplasty was developed in France in the 80s, which consists of the percutaneous injection of bone cement in a liquid state in the region of the fractured vertebral body that solidifies inside the vertebra (ALVES *et al*., 2016), providing increased pedicle screw strength in osteoporotic bones. Vertebroplasty helps stabilize the fracture and relieve pain in patients who do not improve with conventional treatment (medications and orthopedic braces). The bone cement restores the biomechanical integrity of the fractured vertebra, restoring rigidity, robustness and reducing bone deformation (AL-ALI *et al.*, 2009).

The most commonly used cement in vertebroplasty processes is Methyl Polymethacrylate (PMMA). However, some limitations of this material are reported, such as the inability to integrate with the native bone and to enhance the regeneration of bone tissue, in addition to presenting excessive stiffness that can cause fracture of adjacent vertebrae (LIEBERMAN *et al*., 2005). Several alternatives aimed at reducing these complications have been suggested, including the use of hydroxyapatite (HAp)-based calcium phosphate cements, because in addition to providing mechanical properties similar to those of PMMA, it is biocompatible with osteocomponent and osteoconductive properties. Turner *et al*. (2003), performed laboratory tests using a HAp-based compound to reinforce pedicle screws and reported an improvement in the stability and fixation of the systems.

Although several studies confirm the safety of the vertebroplasty process, Amaro (2018) and Rauschmann *et al*. (2004), report that the main complication in this procedure is related to the leakage of bone cement out of the vertebral body into the spinal canal or the vertebral venous system, reaching the pulmonary circulation, which can lead to spinal cord compression or pulmonary embolism, respectively. However, the reduction of the risks of cement leakage and the optimization of the vertebroplasty process could happen if the procedure was simulated in the CFD environment in which the distribution of bone cement in the vertebra during a vertebroplasty procedure could be verified.

In addition to the possibility of cement leakage, another major concern for spinal surgeons, have been the search for methods that improve clamping force in patients with osteoporosis (ABOUSAYED *et al*., 2018; DAI *et al*., 2015; HOPPE and KEEL, 2017). In order to solve these problems, some studies were carried out in order to analyze the distribution of bone cement through fenestrated pedicle screws (GONZÁLEZ *et al*., 2018; CHOMA *et al*., 2012; WANG *et al*., 2014), considering that fenestrations tend to concentrate the distribution of cement around the screw, which can promote a greater force to failure than distribution through injection, in addition to reducing the risk of leakage.

Computational models make it possible to simulate the vertebroplasty process in order to analyze what can be done to find the best methods and materials that result in a vertebra with characteristics similar to the vertebra with healthy bone (ERDEM *et al*., 2013; WANG *et al*., 2014).

Based on the research carried out, it was possible to observe that spinal problems affect most people at some point in their lives. This results not only in damage to the individual's quality of life, but also in professional losses, since spinal diseases are one of the most common causes of sick leave, and can also lead to hospitalizations, representing a high social and financial cost to society. Thus, numerical simulations play a significant role in the search for solutions that aim to minimize these problems.

From a social point of view, the risks associated with the patient could be reduced if the distribution of cement in the vertebra was planned before the surgical procedure, which, in turn, requires a better understanding of the behavior of cement flow. Within this context, the use of computer simulation makes it possible to calculate the flow behavior of bone cement, so that the risk of cement leakage could be minimized and the mechanical properties of the treated vertebra could be optimized, thus increasing the chances of success of the procedure.

From a financial perspective, the use of simulations can result in reduced costs associated with medical errors, postoperative complications, and rework. From the simulations, it is also possible to test and improve products related to vertobroplasty and pedicle instrumentation, reducing development costs and improving the safety and efficacy of the devices.

According to the bibliographic survey carried out, it was observed that the vast majority of the reported studies are experimental or use simplified theoretical mathematical models, highlighting the little use of CFD. Finally, no studies were found that analyzed, via CFD, the distribution of polymethylmethacrylate (PMMA) through fenestrated pedicle screws in vertebrae. These facts justify further research with the use of CFDs. In this sense, the objective of this research is to evaluate the distribution of PMMA-based bone cement in vertebrae with low bone quality through pedicle screws with and without frenestrations, through the application of Computational Fluid Dynamics (CFD) techniques.

METHODOLOGY

The research was carried out at the Laboratory of Research in Fluid Dynamics and Imaging (LPFI) of the Academic Unit of Chemical Engineering and at the Computational Laboratory of Thermal and Fluids (LCTF) of the Academic Unit of Mechanical Engineering of the Federal University of Campina Grande.

The physical problem consists of the study of bone cement flow (PMMA) inside a vertebral body (porous medium), initially filled only with bone marrow. It was decided to simulate a vertebra with reduced bone mass due to osteoporosis, since this is one of the main causes of vertebral fractures that lead to the need to implement the bone cementation process, which is responsible for enabling the filling of injured vertebrae and fixing implants in the spine. For the simulation, the injection of bone cement inside the vertebra was performed through pedicle screws with and without fenestrations. In this sense, the study domain corresponds to a cross-section of the vertebral body of the third lumbar vertebra.

Initially, a bibliographic study was carried out of some mathematical models in the literature capable of predicting the behavior of bone cement flow (PMMA), from its injection through pedicle screws inside the vertebra (porous medium). The flow inside the vertebra was calculated by numerical methods using Computational Fluid Dynamics (CFD). At first, the geometry and the domain of the flow of interest, its boundary conditions and the physical phenomena involved were identified. Then, the flow domain was discretized in a computational mesh and a mathematical modeling capable of representing the behavior of bone cement flow in the vertebra during the cement injection procedure through pedicle screws was described.

In this work, the ANSYS WORKBENCH work environment was used for the development of the simulation steps. Initially, for the construction of the two-dimensional (2D) and three-dimensional (3D) geometry, the ANSYS DESIGN MODELER was used, the mesh generation was performed in the ANSYS MESH software. In the next step, in order to process the simulation, the equations of interest and the mathematical models were chosen according to the type of fluid and physical phenomena involved. For the simulation, the ANSYS FLUENT commercial package was used, in which the flow governing equations were iteratively solved by the finite volume method.

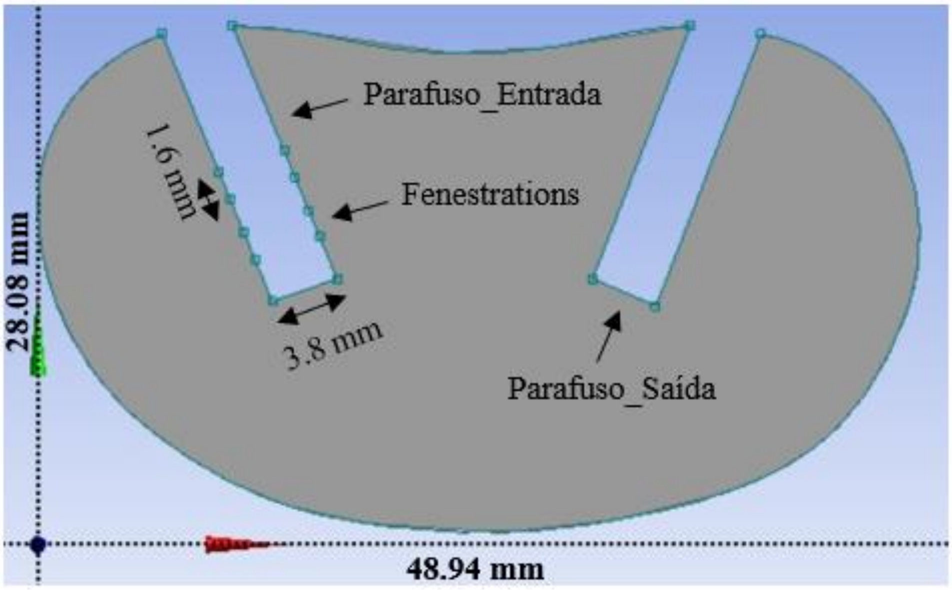
Different numerical simulations were carried out using the FLUENT program, which allowed to study, evaluate and analyze the results obtained from the perspective of CFD. The results generated were compared with the experimental data reported in the literature in order to validate them.

COMPUTATIONAL DOMAIN

The construction of the geometry was carried out in DESIGN MODELER, version 2021 R2, a *commercial software* that belongs to the company ANSYS. In this work, some simplifications were considered during the development of geometry in view of the complexity and variation from one vertebra to another. The dimensions of the vertebral body were obtained from the collection of points on the perimeter of the vertebral body, adopting the same criteria used by Justino and Farias Neto (2018). During the construction of the geometry, in addition to inserting the screw through which the bone cement would be injected, a second screw was inserted in order to relieve the pressure inside the vertebra. The inclusion of the second screw was determined based on the study by Justino and Farias Neto (2018), who observed that as the cement was injected, the internal pressure increased considerably and this was justified by the fact that the bone tends to become increasingly saturated with cement and the liquid initially inside the vertebra tends to compress, increasing the internal pressure progressively.

PMMA (Poly-Methyl Methacryalto) was used as bone cement to carry out the simulations and the physical data provided by the research of Silva (2016) and Loeffel *et al*. (2008). According to Zhou *et al*. (2000), the dimensions considered correspond to an L3 lumbar vertebra. Figure 2.1 shows the geometric shape of the vertebral body in a two-dimensional domain with length and height equal to 48.94 and 28.08 mm, respectively, and the diameters of the holes through which the bone cement was injected into the vertebra (porous medium), the screw has an internal diameter of 3.8 mm and the holes of the fenestrae 1.6 mm. These dimensions are based on the research of Vendrame (2008).

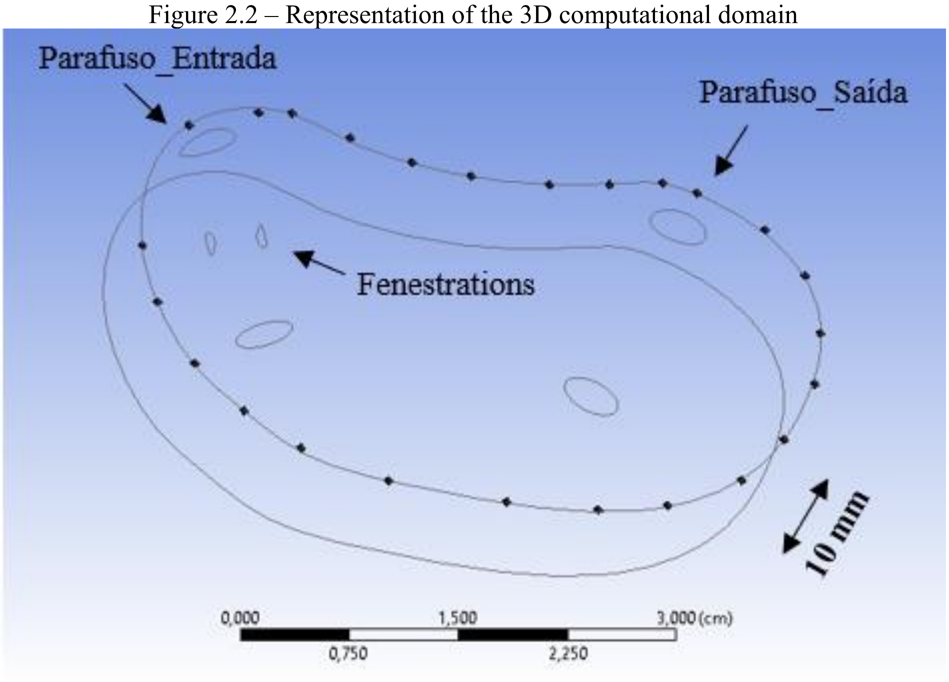
Figure 2.1 – Representation of the 2D computational domain and its dimensions



Source: The author (2022).

From the two-dimensional geometry (Figure 2.1), a 3D geometry with a thickness of 10 mm was constructed, as illustrated in Figure 2.2.

Figure 2.2 – Representation of the 3D computational domain



Source: The Author (2024).

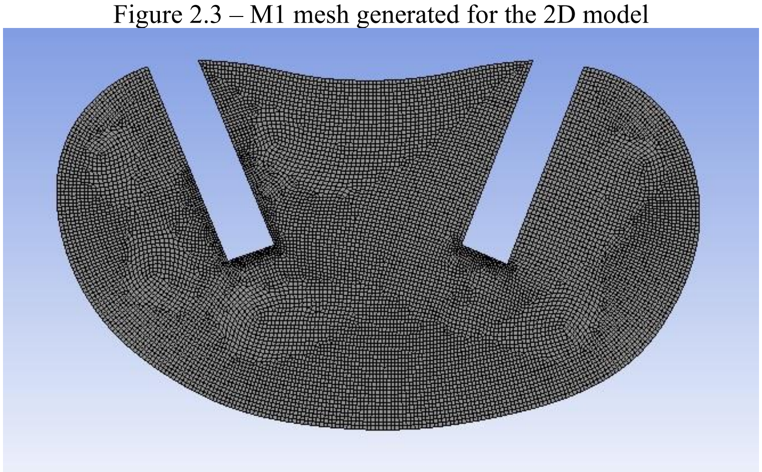
NUMERICAL MESH

The generation of the mesh over the study domain (vertebral body) was performed with the aid of the ANSYS MESH software, in the 2021 R2 version. To ensure that the mesh leads to coherent numerical results with less computational effort, the mesh dependence study was carried out, which consists of a successive refining of an initially coarse mesh to a finer one, until the variation of the variables of interest is minimal or zero.

Three numerical meshes were generated for each 2D and 3D geometry, with different refinements to obtain a good distribution of the elements over the study domain. The three meshes created are represented by M1 (more refined), M2 (intermediate), and M3 (less refined). The analysis of mesh quality was performed using the Mesh Convergence Index (MCI) method, proposed by Roache (2004), in order to show that meshes with different refinements allow results that are not different within the criteria used. The meshes were generated with refinement ratios between the M1 and M2 meshes of 1.5 for the 2D model and 1.6 for the 3D model, and between the M2 and M3 meshes equal to 1.9 for the 2D model and 1.4 for the 3D model (ROACHE, 1994; NUNES *et al.* 2021).

Quadrilateral and tetrahedral elements were used for the 2D and 3D models, respectively. Applying the *Sizing* tool, provided by the MESH software, the input parameter for the element size was defined, where an *element size* of 0.3 mm was defined for the M3 mesh, 0.15 mm for the M2 mesh and 0.1 mm for the M1 mesh, for the 2D model. In order to more accurately capture the spreading profile, especially at the screw inlets. In Figure 2.3, it is possible to observe some details of the M1 mesh composed of quadrilateral elements with the presence of a greater refinement in the input screw.

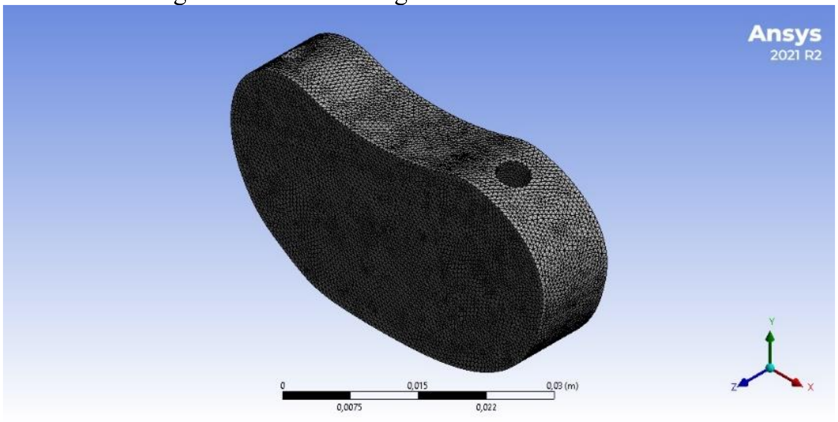
Figure 2.3 – M1 mesh generated for the 2D model



Source: The author (2022).

For the 3D model, an *element size* of 1.2 mm was defined for the M3 mesh, 0.8 mm for the M2 mesh and 0.5 mm for the M1 mesh. Details of the M1 mesh used in the 3D model can be seen in Figure 2.4.

Figure 2.4 – M1 mesh generated for the 3D model



Source: The Author (2024).

Then, some cases were simulated for each of the generated meshes, under the same initial and boundary conditions. At the end, the variation of some variables chosen to evaluate the independence of the results in relation to the meshes considered were analyzed, in order to choose the mesh that presented better results with less computational effort.

Numerical simulations were performed by establishing convergence criteria that determine when a solution is reached, so the *solver* can stop iterating. *Root Mean Square* (RMS) residuals are one of the most important convergence criteria, since they directly relate whether the equations have been solved accurately (Versteeg and Malalasekera, 2007). In this study, a convergence criterion of 10-4 was used for the residuals of all resolved variables.

It was verified, from the mesh convergence study, that among the meshes analyzed, the most refined meshes M1 generated with 104054 elements for the 2D model and 656785 elements for the 3D model were the ones that generated the best results, and these were the ones chosen for the simulations.

MATHEMATICAL MODELING

To perform the modeling, the 2021 R2 version of ANSYS FLUENT® was used with the double precision option enabled. The pressure method was used to solve the transport equations (*pressure-based solver*) for the transient model, the Eulerian-Eulerian approach was also adopted with the following considerations:

A) Laminar and transient biphasic flow regime (bone marrow and bone cement);

B) Incompressible and Newtonian fluid;

C) There is no transfer of mass and heat;

D) The porous medium has isotropic distribution of pores and permeability;

E) The fluid volume model (VOF) was adopted.

Based on these considerations, Equations 2.1 and 2.2 represent the equations of conservation of mass and quantity of motion and reduce to:

$$\frac{\partial(\rho\gamma)}{\partial t} + \nabla.\left(\rho K\vec{U}\right) = 0. \tag{2.1}$$

$$\frac{\partial(\rho\gamma\vec{U})}{\partial t} + \nabla.\left[\rho(K\vec{U}) \otimes \vec{U}\right] - \nabla.\left[\mu_e K\left[\nabla\vec{U} + \left(\nabla\vec{U}\right)^T\right]\right] = \gamma S_M - \gamma\nabla\rho + \vec{F} \tag{2.2}$$

where μ_e is the effective viscosity. S_M corresponds to the term source of momentum in the porous medium given by Equations 2.3, 2.4 and 2.5.

$$S_{M,x} = -\frac{\mu}{K_{perm}}\vec{U}_x. \tag{2.3}$$

$$S_{M,y} = -\frac{\mu}{K_{perm}}\vec{U}_y. \tag{2.4}$$

$$S_{M,z} = -\frac{\mu}{K_{perm}}\vec{U}_z. \tag{2.5}$$

where K_{perm} is the permeability of the porous medium, $\vec{U}_i$ the velocity in the direction $i.(x, y, z)$

The interfacial forces acting are calculated from $\vec{F}$ data by Equation 2.6

$$\vec{F} = \sigma\frac{\rho k\nabla\alpha}{\frac{1}{2}(\rho_1 + \rho_2)} \tag{2.6}$$

where is the surface tension and σk the local curvature.

The effect of surface tension between fluids is included in the VOF model. In this research, the model applied was the continuous surface force (CSF). The addition of surface tension to the VOF calculations results in a source term in the equation of the amount of motion, as presented in Equation 2.6. In this case, we considered the constant surface tension $0{,}033\ N/m$ along the interface, so that only the normal force acts on the interface.

Interface tracking is performed from the VOF model. Thus, due to the simplifications adopted, the continuity equation for the volumetric fraction of one or more phases is given by Equation 2.7.

$$\frac{1}{\rho_q}\left[\frac{\partial}{\partial t}\left(\alpha_q\rho_q\right) + \nabla.\left(\alpha_q\rho_q\vec{v}_q\right)\right] = 0. \tag{2.7}$$

The volumetric fraction equation is solved based on the constraint established by Equation 2.8.

$$\sum_{q=1}^{n}\alpha_q = 1. \tag{2.8}$$

The interface tracking model used was the *Sharp*, which treats the interface without considering the detachment of particles, considering that it was considered a laminar flow and a fluid with high viscosity.

Because there is neither PMMA, trabecular bone, nor spinal cord in the simulator database, the components were created according to the physical properties shown in Table 2.1.

Table 2.1 – Parameters and properties of the vertebra and PMMA

Vertebra	Porosity	0,911 (Baroud *et al.*, 2006)
	Permeability	9,7 $10\times^{-8}$ m2 (Baroud *et al.*, 2006)
PMMA	Density	1180 kg/m3 (Silva, 2016)
	Viscosity	100 Pa.s (Loeffel *et al.*, 2008)
Bone marrow	Density	1043 kg/m3 (Joar *et al.*, 1993)
	Viscosity	1 Pa.s (Bohner *et al.*, 2003)

Source: The author (2022).

The data were inserted to represent the properties of the vertebra so that it was possible to simulate a vertebra with osteoporotic characteristics. According to Baroud *et al*. (2006), in healthy bone porosity can be as low as 75% and in osteoporotic bone as high as 95%. In their paper, Baroud *et al*. (2006) adopted a porosity of 91.1%, which corresponds to the porosity of an osteoporotic vertebra. The empty spaces are filled with bone marrow. According to Nauman *et al*. (1999), intertrabecular permeability is not well characterized or understood, due to the structural anisotropy of the trabecular bone and the wide range of existing trabecular architectures. Baroud *et al*. (2006), obtained values for permeability of 1.9 and 9.7 10-8× m2, the lowest value of 1.9 is representative of the low permeability of healthy bone, while the highest value describes the high permeability of osteoporotic bone.

In all simulations, the parameters were defined in *the* software *solver* as shown in Chart 2.1.

Table 2.1 – Parameters used in the simulations

General conditions	
Type of flow	Biphasic
Flow regime	Transient and Laminar
Multiphase model	*Volume of Fluid* (VOF)
Gravitational force	Considerada -9,81 m/s2
Convergence criterion	1.0.10-4
Pressure-speed coupling	*Coupled*
Surface Tension Model	*Continuous Surface Force* (CSF)
Solver	Pressure-based
Discretization	*Gradient = Least Squares Cell Based* *Pressure = SOON!* *Momentum = Second Order Upwind* *Volume Fraction = Compressive* *Transient Formulation = First Order Implicit*
Time Passage	0.1 s
Loops for each iteration	100
Total Simulated Insertion Time	120 sec.

Source: The author (2022).

INITIAL AND BOUNDARY CONDITIONS

As an initial condition for the transient regime, the porous domain (vertebra) was initially filled only with bone marrow, i.e., a volumetric fraction of bone marrow equal to 1, a pressure equal to 1 atm and zero medulla velocities.

In the internal walls, the condition of non-slip wall was considered, i.e., close to the walls the velocities are zero in all directions. At the outlet, the condition used was the *pressure outlet*, so that the assumed pressure gain was 0 Pa. In the inlet section, the pressure condition was adopted as a function of the PPMA injection time, given by Equation 2.9

$$P = 3{,}2803t + 3{,}9512 \quad (2.9)$$

where P is the pressure on MPa in a time interval t of 5 min.

Equation 2.9 was obtained from the adjustment with the results of the pressure determined numerically and analytically by Baroud and Yahia (2004), who proposed a rheological model to describe the behavior of PMMA flow.

The PMMA is injected gradually, the simulation is conducted under a transient regime, the cement flow through the screw was simulated during a period of 120 seconds based on the study by Baroud and Yahia (2004).

RESULTS AND DISCUSSIONS

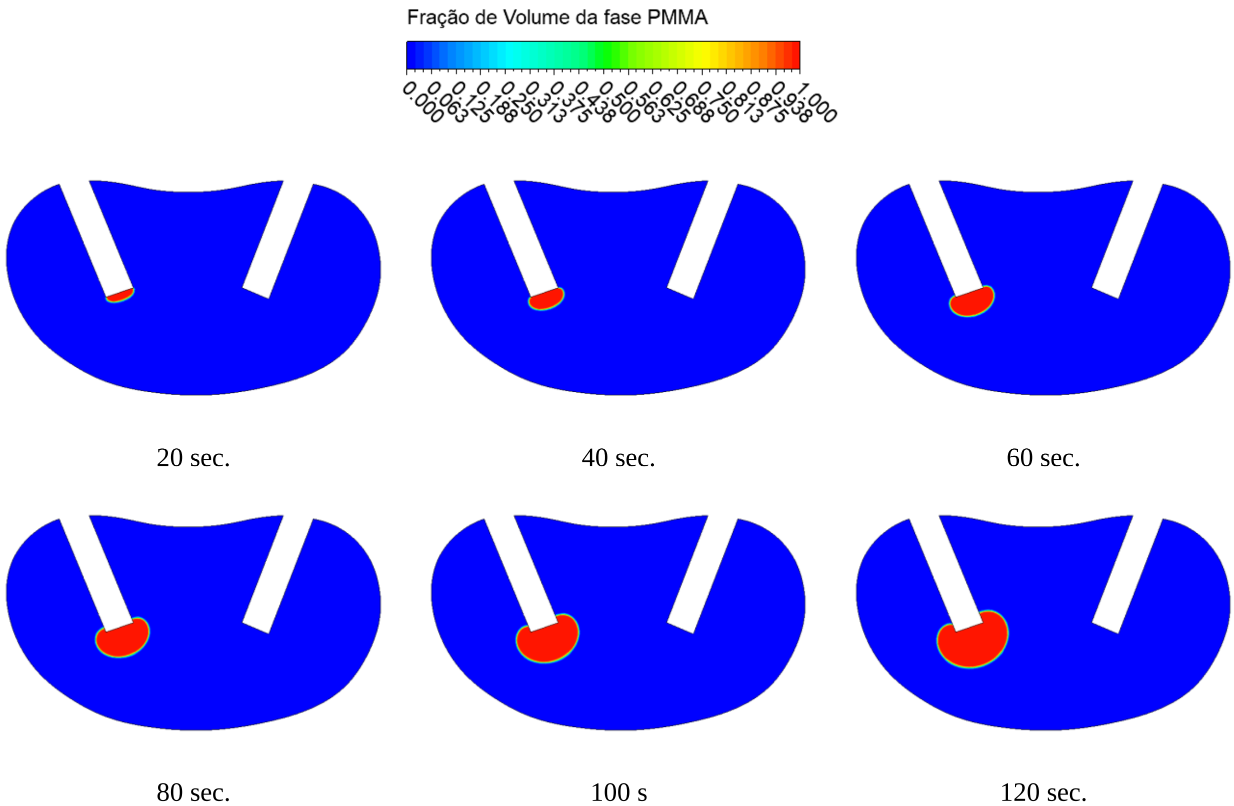
To evaluate the distribution of bone cement in vertebrae through pedicle screws with and without fenestrations, simulations were performed considering the mathematical modeling and the initial and boundary conditions explained in Sections 2.3 and 2.4, as well as the parameters and properties described in Table 2.1 and Chart 2.1. In order to evaluate the mathematical modeling used, the results were compared with experimental data available in the literature, always highlighting the simplifications adopted.

ANALYSIS OF PMMA DISTRIBUTION THROUGH SCREWS WITH AND WITHOUT FENESTRATIONS

In order to understand the behavior of bone cement flow in the vertebra and to compare the results of injection through cannulated pedicle screws with and without fenestrations, Figures 3.1 and 3.2 show the evolution of the distribution of the volumetric fraction of bone cement over a plane inside the vertebra as a function of time for cannulated pedicle screws with and without fenestrations. respectively.

Figure 3.1 shows the evolution of the volumetric fraction of PMMA as a function of time, at different time intervals 20, 40, 60, 80, 100 and 120 seconds, for cement injected through a cannulated screw without fenestrations.

Figure 3.1 – Evolution of PMMA injection through screws without fenestration over time

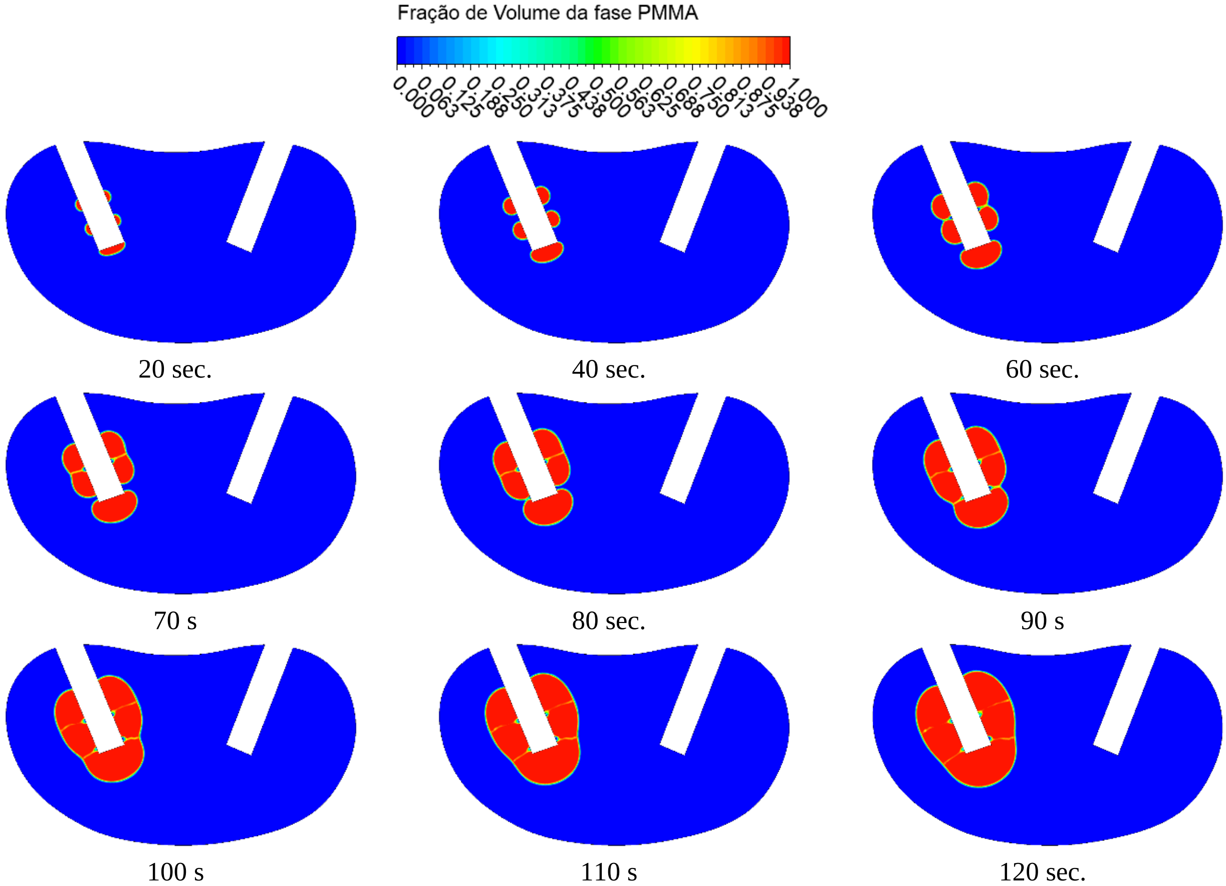


Source: The author (2023).

It has been observed that as the cement is injected over time, most of the cement concentrates at the tip of the screw, tending to a spherical shape distribution.

Figure 3.2 shows the evolution of the volumetric fraction of PMMA as a function of time, for the different time intervals 20, 40, 60, 70, 80, 90, 100, 110 and 120 seconds, with the cement injected through a cannulated screw with fenestrations.

Figure 3.2 – Evolution of PMMA injection through screws with fenestrations over time



Source: The author (2023).

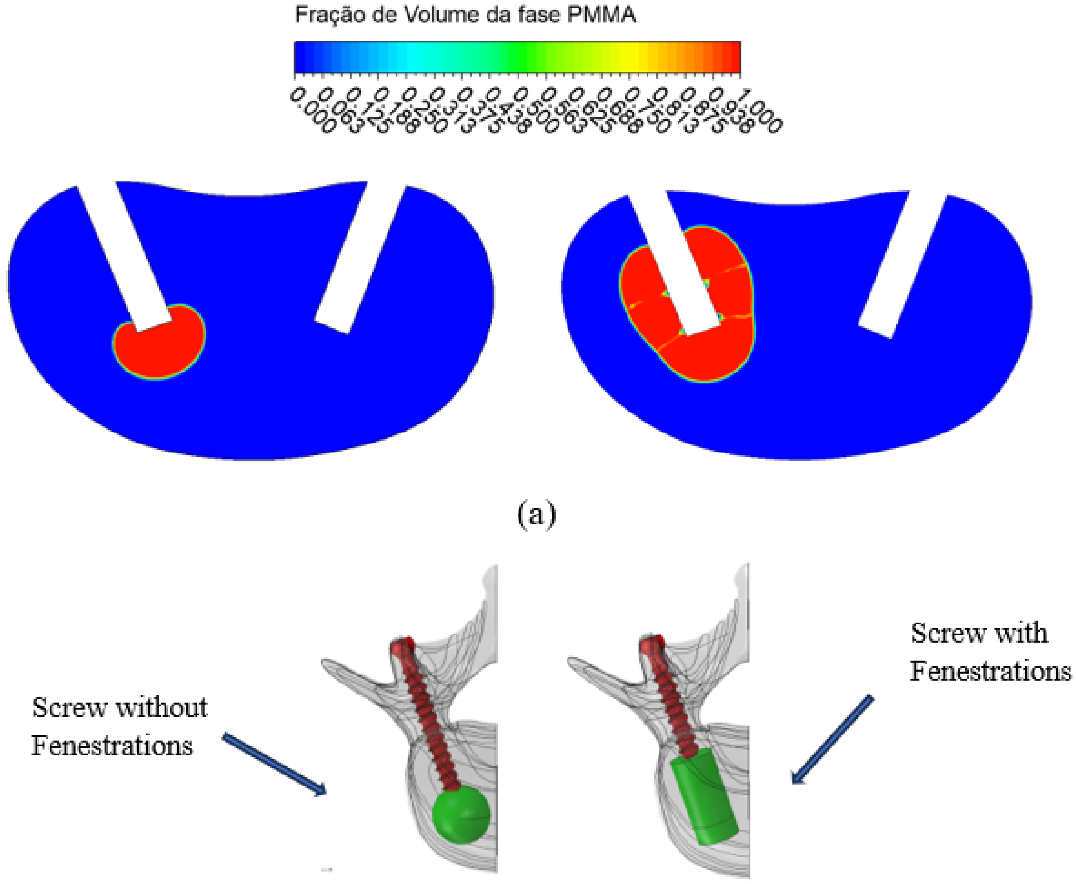
It is observed that over time the cement tends to concentrate around the pedicle screw nail, involving the entire screw, which is in agreement with what is reported in the literature, as reported by Wang *et al*. (2014) who report that, when injected through a pedicle screw with fenestrations, the PPMA presents itself with a cylindrical shape surrounding the screw, instead of being associated mainly with the tip of the screw. At 60 seconds it is already possible to observe that the cement has a tendency to spread in a more cylindrical way around the screw.

The results of the present analysis indicate that when fenestrated screws are used, even injecting a smaller amount of cement, the fact that the fenestrations allow the injection through the screw shank allow a more uniform spread around a larger area of the screw, a behavior that can promote greater stability than that observed in pedicle screws with a single cement entry at the tip of the screw. which corroborates the results reported by González *et al*. (2018), which states that the way the cement is distributed around the screw directly influences its retention strength.

These results also confirm those reported by Liu *et al*. (2016), who reported that, in relation to the stability of a screw with fenestrations, no significant difference was observed when injecting larger and smaller amounts of cement around the screw, indicating that the way PMMA is distributed is more important than the amount of cement injected.

Figure 3.3-(a) compares cement injection through screws with and without fenestration at 120 seconds of simulation. Figure 3.3-(b) shows the behavior of cement spreading through screws with and without fenestration reported by Wang *et al*. (2014).

Figure 3.3 – Comparison of PMMA injection through screws with and without fenestrations: (a) obtained in the simulations and (b) obtained by Wang *et al*. (2014)



(b)

Fonte: (a) A autora (2023) e (b) Wang *et al*. (2014).

Comparing the contours of the fraction of volume of PMMA injected through screws with and without fenestrations, observed in Figure 3.3-(a), it is visible that in the screw with fenestrations, the cement involves a larger area of the screw, presenting a shape that is close to that of a cylinder, compared to the screw without the fenestrations where the cement spreads more spherically. This behavior coincides with that reported by Wang *et al*. (2014), who observed that when cannulated and fenestrated screws are used, the cement tends to be located in a cylindrical area around the screw, rather than concentrating at the tip of the screw, as illustrated in Figure 3.3-(b).

The results of this analysis indicate that the injection of bone cement through pedicle screws with fenestrations can be used as an auxiliary method to improve screw fixation, especially in osteoporotic bones, since the fixation power of the screw in osteoporotic bone is reduced with the decrease in bone mineral density.

Table 3.1 shows the area A_s invaded by cement when injected through screws with and without fenestrations.

Table 3.1 – Area of the cement plume injected through screws with and without fenestrations

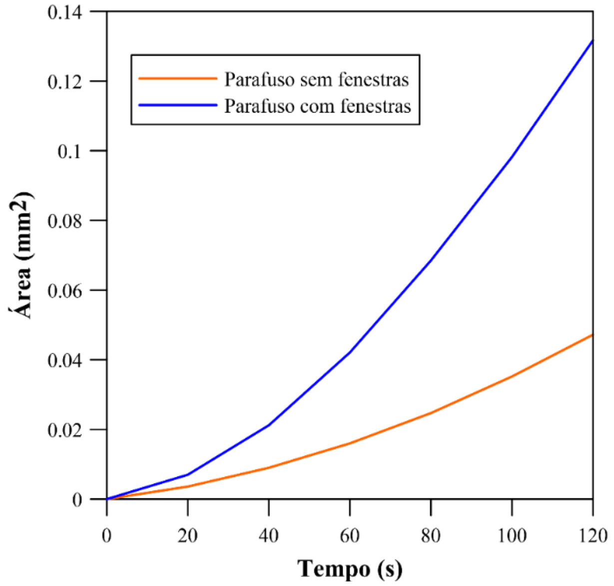
Time(s)	Screw without fenestration (mm2)	Screw with fenestrations (mm2)
20	0,0036	0,0070
40	0,0090	0,0212
60	0,0160	0,0421
80	0,0247	0,0685
100	0,0352	0,0982
120	0,0472	0,1317

Source: The author (2023).

As predicted, cement delivery is most effective when being injected through fenestrated pedicle screws. This is because fenestrations in the screws allow for more efficient dispersion of the bone cement by increasing the contact area between the cement and the surrounding bone tissue. As a result, the same amount of cement can be distributed more evenly and quickly, speeding up the surgical procedure. In addition, greater efficiency in the delivery of cement can contribute to a more robust fixation of the screws and a better biomechanical stability of the vertebra after the procedure. This advantage can be especially significant in patients with osteoporosis or other conditions that compromise bone density, where achieving a solid fixation of the screws is crucial to avoid postoperative complications. Therefore, the use of fenestrated pedicle screws not only reduces the time required for cement administration but can also improve the overall quality of the procedure.

Figure 3.4 shows a comparison of the area obtained from the injection through pedicle screws with and without fenestrations.

Figure 3.4 – Area as a function of time of the cement plume injected through screws with and without fenestrations



Source: The author (2023).

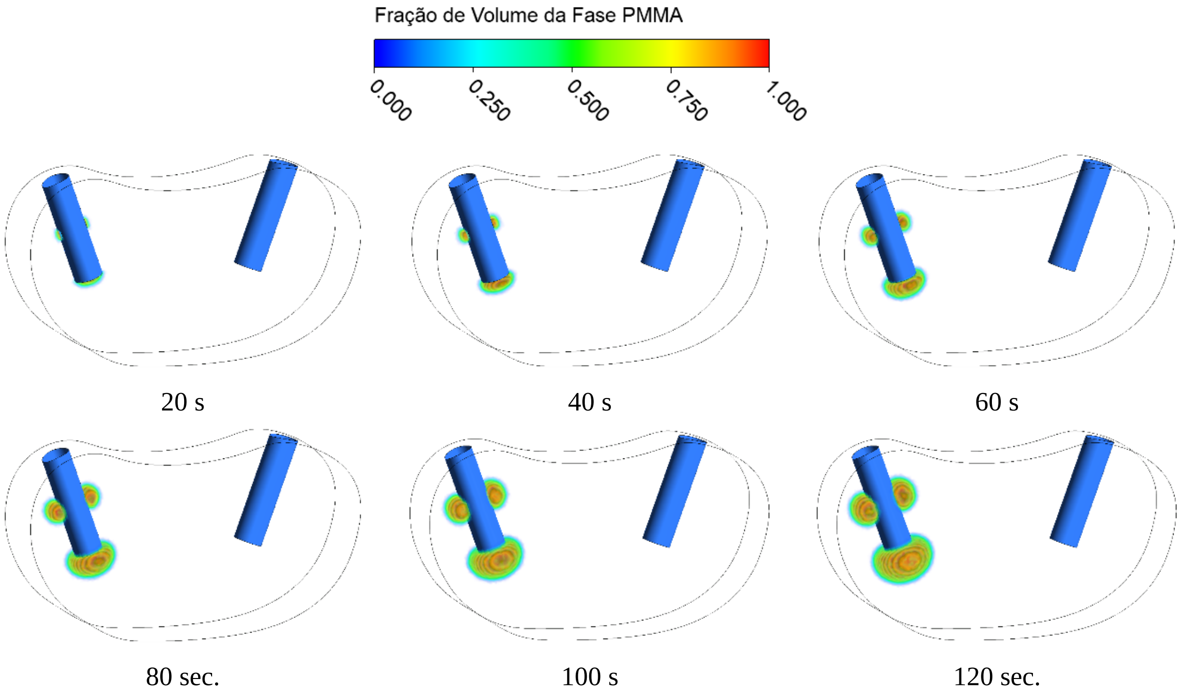
It can be seen that at the beginning of the injection, screws with or without fenestrations do not present great variations in the area of the cement plume. However, over the injection time, the curves are further apart, presenting a greater discrepancy, and it is possible to observe that the area invaded by the cement is significantly larger when the cement is injected through the fenestrated screw. Figure 3.4 also confirms that the use of fenestrated screws can reduce the time needed to inject larger amounts of cement.

The biggest concern with cement injection is the possibility of leakage that can cause various damages to the patient's health, and larger amounts of cement increase the risk of leakage. Baroud *et al*. (2006), indicate that increasing the viscosity of cement can reduce the chances of leakage. On the other hand, it can also excessively increase the injection pressure of the cement. In this sense, cement injection through several fenestrated holes can reduce the cement injection pressure. These results suggest that the risk of cement leakage can be reduced with the application of a more viscous cement by means of fenestrated screws, without compromising the fixation strength of the screw.

INFLUENCE OF SCREW FENESTRATIONS ON PMMA DISTRIBUTION

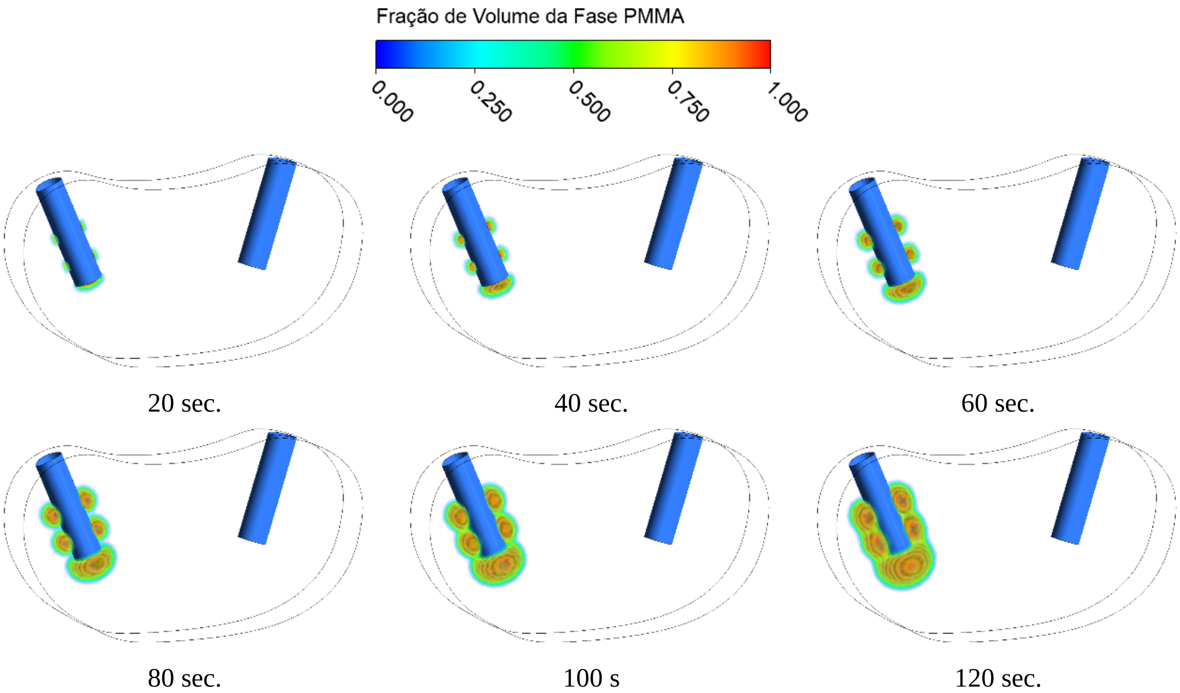
Simulations were performed to evaluate the distribution of bone cement injected through cannulated screws with two and four fenestrations. Figures 3.5 and 3.6 show the evolution of the volumetric fraction of PMMA as a function of time, at different time intervals of 20, 40, 60, 80, 100, and 120 seconds, for these two types of screws.

Figure 3.5 – Evolution of PMMA injection through a screw with 2 fenestrations over time



Source: The Author (2024).

Figure 3.6 – Evolution of PMMA injection through screw with 4 fenestrations over time

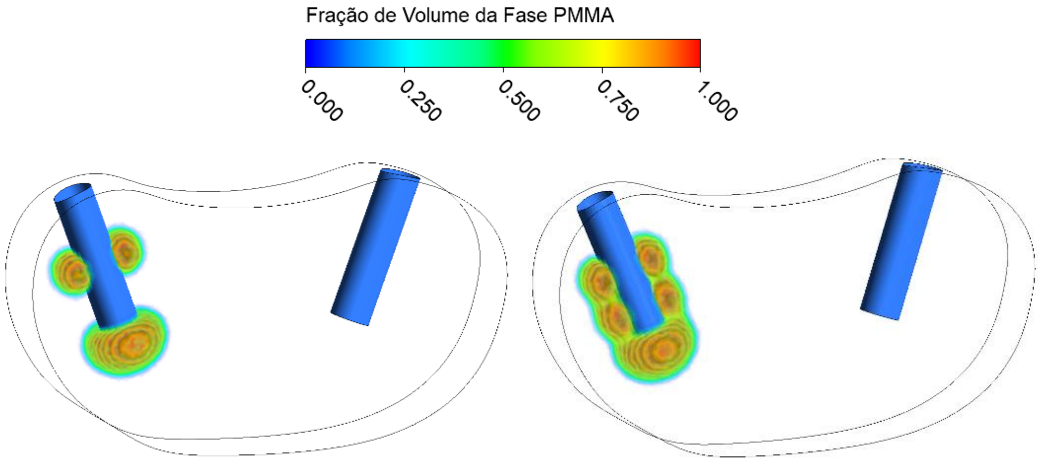


Source: The Author (2024).

As can be seen in Figures 3.5 and 3.6, for both screws, the cement was evenly distributed around the screw shank, however, in the screw with more fenestrations, the cement involved a larger area of the stem. The behavior observed when the cement is injected through the screw with 4 fenestrations, may contribute, according to the literature, to favor a better fixation of the screw by allowing it to have a larger area involved by the cement in the same time interval. Thus, the use of screws with a higher number of fenestrations can contribute to avoid any movement or displacement of the screw from its original position, and the number of fenestrations will depend on the non-compromise of the screw's resistance so as not to suffer rupture in view of the fenestrations.

Figure 3.7 compares the bone cement distribution profiles in the vertebra at 120 seconds for a screw with two and four lateral fenestrations.

Figure 3.7 – Comparison of PMMA injection through screw with 2 and 4 fenestrations



Source: The Author (2024).

When comparing the contours of the fraction volume of PMMA injected through screws with two and four fenestrations, it is observed that in the screw with four fenestrations, the cement surrounds a larger portion of the screw in the same time interval, presenting a shape similar to what was observed in the two-dimensional case study.

Although in this study the position of the lateral screw holes was kept constant, the results presented indicate that the positioning and number of screw holes can modify the flow and distribution of cement, corroborating the study by Chen *et al*. (2005), who experimentally evaluated the distribution of bone cement in cannulated screws with different numbers of lateral holes. The authors concluded that bone cement flowed predominantly from the proximal lateral holes, while almost no cement flowed from the distal holes, i.e., different numbers of fenestrations produced distinct cement flows.

Thus, the number of screw fenestrations is a factor that must be taken into account when performing the bone cement injection procedure. The design of new screws with optimized holes (number, size and position) taking into account the internal microarchitecture of each vertebra could provide a more uniform flow of cement around a larger area of the screw, thus improving its fixation. In addition, fenestrated screws have the ability to limit the injection of cement into the vertebral body, making it possible to use smaller amounts of cement without compromising fixation, which can provide greater security against cement leakage out of the vertebral body.

One concern regarding fenestrations of a cannulated screw is that it can weaken the screw shank, decreasing the screw's ability to resist pullout forces. On the other hand, when cement is injected, a portion of that cement stays inside the fenestrated bolt and the rest surrounds the bolt. This behavior can mitigate possible weaknesses related to the shank of screws with fenestrations, the effects of these variables that can affect the fixation capacity of the screw can be the subject of future studies.

CONCLUSION

From the results obtained, it was possible to conclude that the proposed mathematical model was able to predict the behavior of bone cement distribution through pedicle screws in the vertebra. This computational approach not only allows for a detailed and predictive analysis of bone cement flow, but also provides a platform for the exploration of different surgical scenarios and the assessment of potential consequences, thereby contributing to significant advances in medical practice. This predictive capability is critical for the optimization of surgical procedures, allowing surgeries to be planned in advance and adapting their techniques to ensure optimal bone cement distribution, thereby minimizing the risk of postoperative complications and maximizing clinical outcomes for patients.

Regarding the use of screws with or without fenestrations, it was observed that by opting for fenestrated screws, it is possible to inject smaller amounts of cement without compromising the fixation of the screw, a fact that can provide greater security against cement leaks out of the vertebral body. In addition, the results indicate that the positioning and number of fenestrations of the screws can modify the flow and distribution of bone cement in the vertebra, providing a significant influence on postoperative biomechanical stability and fixation efficacy.

Finally, the injection of bone cement into vertebrae through pedicle screws with fenestrations emerges as a potentially safer alternative to surgical procedures in the spine, presenting an approach that can reduce the risks and complications associated with cement injection. This technique is potentially useful in cases involving osteoporotic vertebrae, where the incidence of cement leaks is higher and screw fixation is more challenging due to low bone mineral density.

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