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ORIGINAL ARTICLE

Effect of uncertain quantities on the stability analysis of a miniscrew anchorage system

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ABSTRACT

Purpose: To determine how the uncertainties related to both the material properties and failure threshold value affect the failure prediction of a miniscrew using the FE analysis.
Materials and Methods: Three-dimensional surface models for molar, and premolar, segments of the mandibular bone surrounding these two teeth were generated using patient-specific CT data. The 3D model was exported to a finite element Ansys/Workbench to conduct a static analysis with the traction load of 2 N exerted on the miniscrew. The probabilistic analysis was carried out to determine the failure of the miniscrew, in which Kriging was selected as the metamodeling method.
Results: The uncertainties related to material properties significantly affect the failure probability of the miniscrew, especially for the values with a higher percentage of variability. The analyses in which a constant threshold value is considered indicate no failure, whereas the probabilistic analysis in which the random effect of the threshold value is considered yields a failure probability for the miniscrew.
Conclusion: To accurately evaluate the stability of a miniscrew from an FE analysis, the computation of the failure probability of the miniscrew should take into account the uncertainty regarding the threshold value.

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Miniscrew failure; finite element analysis; probabilistic analysis

Introduction

Orthodontic miniscrews have often been used as orthodontic anchorage for many years [1]. However, miniscrews tend to demonstrate a higher failure rate than implants used for other orthodontic treatments. The failure rate has been reported as high as 25% in the literature [2].

The parameters affecting a miniscrew failure can be examined using the finite element method (FEM) [3]. In a finite element analysis (FEA), results similar to the observations from clinical applications mainly depend on the material models for bones, the boundary conditions applied to the model, and contact definition at the interface between bone and implant [4].

Since patient-specific bone models are generated using patients' CT images, a similar approach has been recently applied to map the material properties of the bone from bone mineral density obtained from CT images and then to use empirical relations to assign material properties such as Young's modulus to the bones concerned [5]. The elasticity-density relationship given in the literature indicates substantial differences, leading to different FEA simulation results [6]. Therefore, this paper aims to determine how these uncertainties related to the material properties of bones affect the FEA results that have been widely utilized to evaluate the success rate of a miniscrew.

No critical displacement value has been specified in the literature, which might be used to predict the primary stabilization of the miniscrew [7]. In a study by Yeh and Keaveny [8], micro-damage in the cancellous bone can occur at a relatively low value of 2000μstrain, while [9],give a value of 5785μstrain [9]. Different strain values taken as criteria may lead to difficulties in evaluating the results from the FEA to provide clinicians with how they can be sure whether the location of the miniscrew inserted is the best place in terms of the stability of a miniscrew. Accurate information regarding the effect of bone characteristic, bone-implant interface and acceptable amount of force is still lacking in the literature [10].

To consider the uncertainty related to the parameters indicating the stability of a miniscrew, a probabilistic approach might seem an appropriate tool to evaluate the results from an FEA. The use of probabilistic approaches to include bone material properties in the predictions of the stability of a miniscrew are particularly relevant as they enable consideration of the impact of intersubject variability reported in the literature.

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In a few studies, the probabilistic approach is utilized either to include the random effects of the parameters in the FEA [11], or to evaluate the results in probabilistic terms [9]. However, these studies take a deterministic failure threshold, which has a single value that does not consider any uncertainty. Since there is a large variation, this study takes the threshold value of the failure as a random variable so that the variation in the value of the allowable strain is taken into account during the FEA. As shown in the analysis of the miniscrew, a constant threshold value indicates no failure, whereas the probabilistic analysis in which the random effect of the threshold value is considered yields a failure probability for the miniscrew. Thus, it can be concluded that the approach utilized in this paper might better estimate the failure of a miniscrew.

Materials and methods

Construction of the three-dimensional model

Three-dimensional (3D) surface models for molar, premolar, segments of bone surrounding these two teeth, which are separately modelled as cortical and cancellous, and periodontal ligament (PDL) of each tooth were generated from patient-specific CT data using MIMICS(Materialize, Belgium). The limit values of the Hounsfield Unit (HU) were determined with a relevant specialist physician to represent the tissues are shown in Table 1.

Materials properties

The material properties are considered random variables, and their parameters are listed in Table 2 [11].

In order to evaluate the variation of the stability of a miniscrew, the coefficient of variation (CV) for the random variables was taken as 5%, 10%, 20%, 30%,40% and %50 to account for the uncertainty.

The other materials in the model, such as teeth, miniscrew and PDL, are considered as deterministic variables since their influence on the failure of a miniscrew is far less than that of the material properties of the bones [12]. Their material properties are taken from the literature [13] and listed in Table 3.

Table 1. Limit values of HU determined according to tissue concerned.

Tissue	Lower HU Value	Upper HU Value
Cortical	226	1200
Cancellous	41	225
Dental	1200	3071

Table 2. Random material properties.

Young's Modulus	Distribution	Mean (MPa)	CV (%)
Cortical	Normal	16,315	14
Cancellous	Lognormal	493	53

CV: coefficient of variation (ratio of standard deviation to mean, expressed as a percentage).

Table 3. Deterministic material properties.

	Elastic modulus (GPa)	Poisson's ratio
PDL	0.069	0.45
Teeth	22	0.31
Miniscrew(Titanium Alloy-Ti-6Al-4 V)	110	0.30

Finite element analysis

A 3D 10-node tetrahedral structural solid with a quadratic displacement behaviour, which is suitable to model irregular meshes such as the model used in this study, was selected as given in Figure 1. The detailed element assignment as well as the skewness value for all the elements in the model are listed in Table 4.

Frictionless contact between the miniscrew and the cortical and cancellous bones was chosen, and the rest of the contacts in the model was assigned as bonded.

A load of 2.0 N was applied to the head of the miniscrew to simulate clinically effective retraction force [14]. The constraints were assigned to all cutting faces, as shown in Figure 2.

Figure 1. Finite element model consisting of separately modelled; miniscrew, tooth, PDL and cortical and cancellous bone elements.

Table 4. Number of nodes and elements in the Finite Element Model.

	Nodes	Elements	Skewness(Average)
Cortical bone	95,171	63,773	0.33
Cancellous bone	122,664	86,053	0.28
Mini screw	32,603	22,342	0.34
PDL(Second Premolar)	8839	4405	0.62
PDL(First Premolar)	20,937	10,431	0.61
Second Premolar	28,755	19,851	0.26
First Premolar	62,296	45,169	0.25
Total	**374,265**	**252,024**	**0.31**

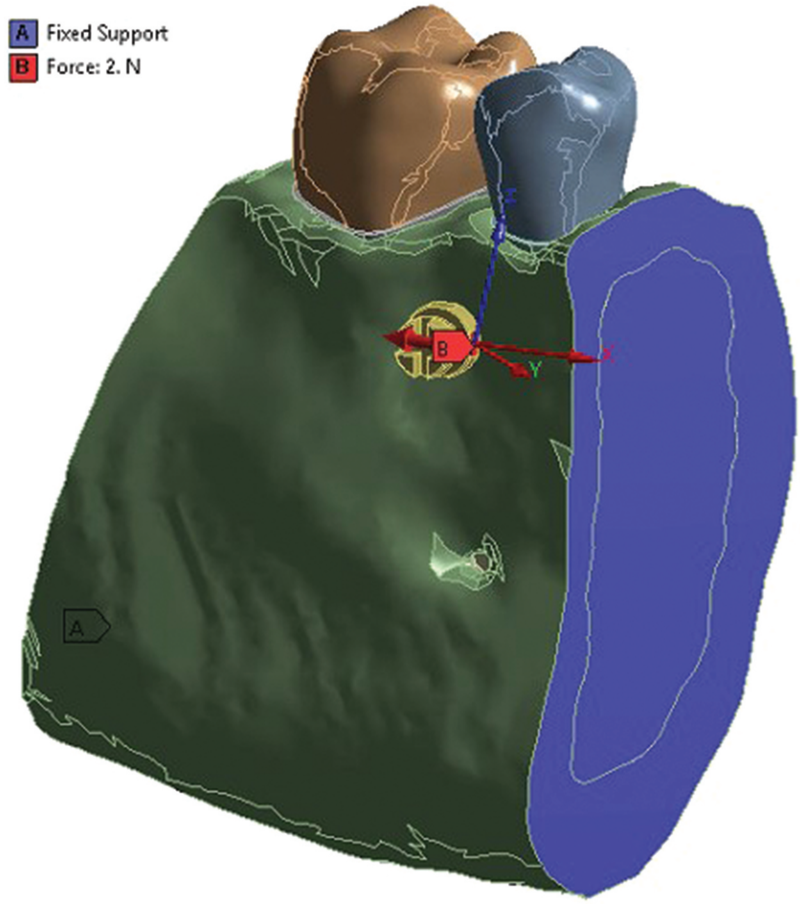

Figure 2. Boundary conditions at the FEA simulation.

Probabilistic analysis

The evaluation of the success of a mini implant using numerical analyses inherently poses variations/uncertainties [15]. The probabilistic approach can be used by which the uncertainties related to the variables are taken into account as random variables with a known probability distribution [16]. In this context, Young's modulus of both cortical and cancellous bones were considered as random variables. The performance function describing the failure of the mini-screw can be written as:

$$g(\mathbf{x}) = \varepsilon_{allowable} - \varepsilon_{max} \leq 0 \quad (1)$$

Where **x** is the vector including the random variables given in Table 2, $\varepsilon_{allowable}$ denotes the random variable describing the allowable strain for the stability of the miniscrew and ε_{max} denotes the maximum principal elastic strain. The allowable strain is considered as normally distributed with a mean value of 4000µstrain and a standard deviation of 1500µstrain to cover a wide range of uncertainty reported in the literature related to the threshold value for the stability of a miniscrew.

The probabilistic tools in ANSYS/Workbench version 16.0 is was utilized to compute the failure probability from the performance function given in Eq.(1). However, using probabilistic methods needs a considerable amount of computational time [17]. Therefore, a meta modelling technique called Kriging was selected, by which a mathematical model is constructed in place of the time-consuming finite element analysis of the mini-screw system [12] .

Results

Results from deterministic FEA

A deterministic FEA was carried out to compare the results reported in the literature to ensure the setup for the FEA simulation is accurate. Considering the deterministic material properties given in Table 2 and 3, the maximum principal strain distribution for the bone-implant model was obtained as shown in Figure 3(a), where, for ease of observation, a cross-section of the FE model is presented in Figure 3(b). The maximum principal strains that occurred at the cortical and cancellous bones are determined as 284.7µε and 1549.4µε, respectively.

As expected, the maximum principal strain occurs at the interface between the tip of the miniscrew and the cancellous bone, which is in accordance with the strain distribution reported in the literature [5,16].

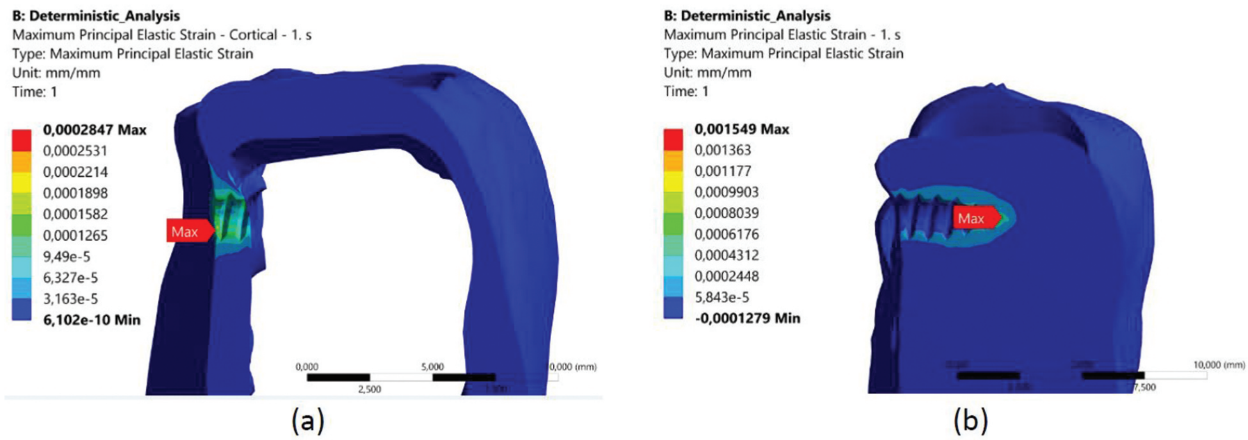

Figure 3. Distribution of the maximum principal strain at the cortical (a) and cancellous bone (b) for the deterministic FEA.

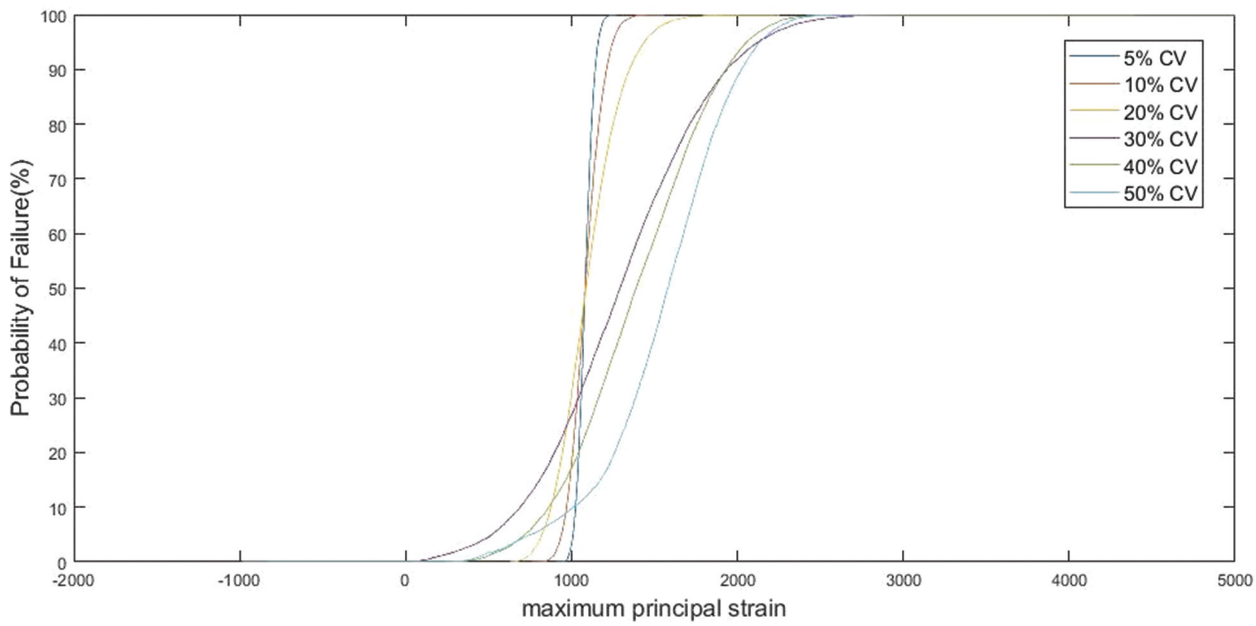

Figure 4. The CDF for the maximum principal strains corresponding to the variations of the material properties of both cortical and cancellous bones.

Results from probabilistic analysis

In order to evaluate how the uncertainty related to the material properties can affect the decision on the stability of the miniscrew, the probabilistic analysis corresponding to 5%, 10%, 20%, 30%,40% and 50% of CVs were taken into account, and the corresponding distribution of the maximum principal strain at the cancellous bone in the mandible are shown in Figure 4.

The extent to which variability in the threshold value of maximum principal strains levels, which are used as an indicator for the failure of a miniscrew in the literature, affects the probabilistic results can be seen in Figure 5. The value of the performance function less than zero indicates the failure of the miniscrew. The comparison of the failure probability of the miniscrew is graphically demonstrated in Figure 6 for all values of CVs considered in this study.

Discussion

The stability and success rate of a miniscrew are among the important factors that are sought for successful clinical applications. Although the development in both bio-materials as well as the design of miniscrews lead to safer and more stable implants, the failure rate is still high, especially in the mandibula compared to the maxilla, as reported in the literature [18] . It has been pointed out that the uncertainties regarding the value and orientation of the load exerted on the miniscrew have the most significant effect on the stability. However, very few studies have concentrated on how the uncertainty of the material properties of both cortical and cancellous bones can affect the results that are extensively used for the assessment of the stability of a miniscrew [19]. Although the studies in the literature consider Young's modulus of both

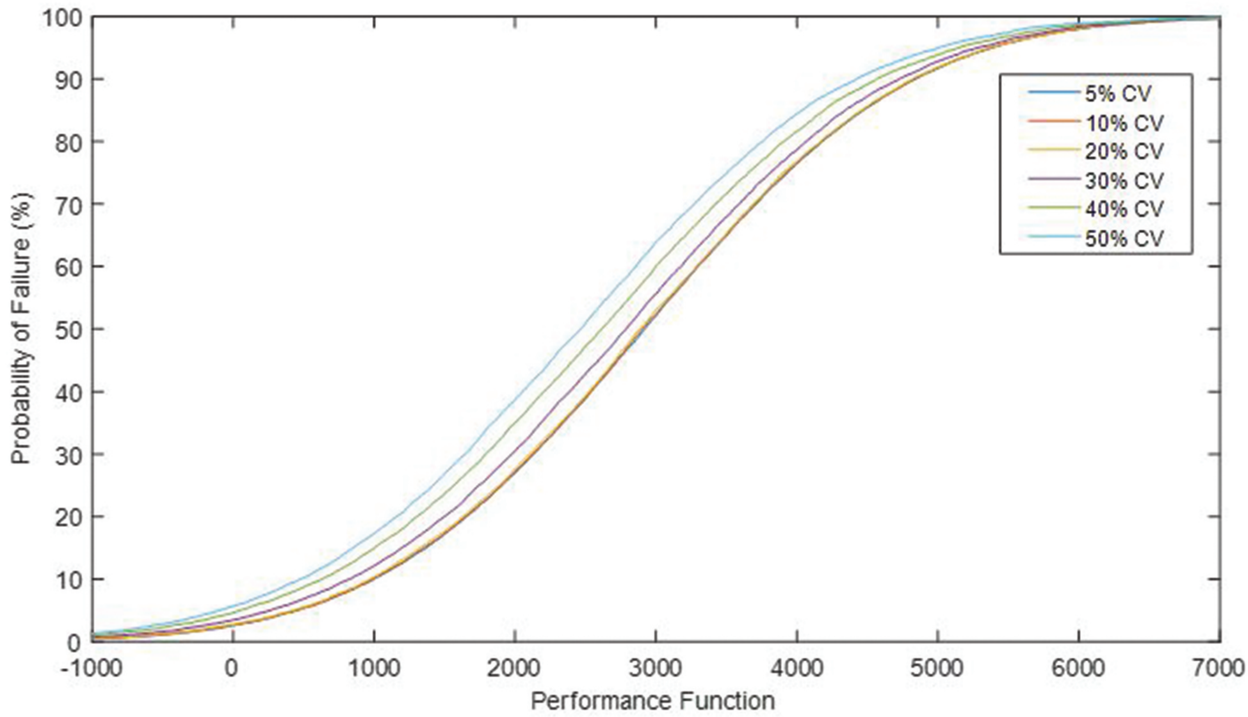

Figure 5. The CDF plots for the performance functions corresponding to the variation of the material properties of both cortical and cancellous bones.

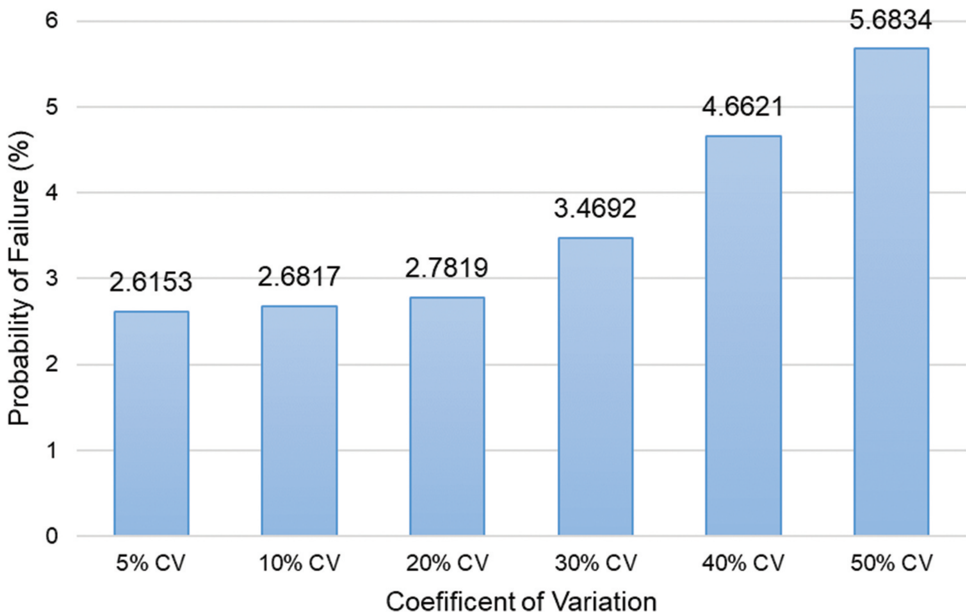

Figure 6. The failure probability of the miniscrew corresponding to the value of CVs.

cortical and cancellous bones as a random variable, a constant threshold value is considered.

As stated in this study, setting a constant threshold value is highly controversial, and a single value has not been accepted yet to assess the results obtained from the FEA in the literature and from a clinical point of view, consideration of uncertainties has a high impact [20, 21]. Therefore, this study aims to demonstrate that even a small amount of uncertainty can highly affect the results that have been utilized widely as an indicator for the failure of a miniscrew. To our knowledge, for the first time in the literature, this study has put forward the effect of the uncertainty regarding the threshold value for the analyses at which uncertainty regarding the parameters such as load exerted on the miniscrew, Young's modulus of the bone are taken into account.

From the FE-based probabilistic analyses carried out in this study, small variations of the material properties of the bones have less effect on the results of the maximum principal strain. However, the variation greater than 20% of CVs may increase the failure rate in almost two-folds, compared to the analyses in which the CV values are lower than 30%.

Having taken into account a constant threshold value of 4000µstrain, the Cumulative Distribution Function (CDF) of the maximum principal strain does not indicate any failure since the threshold value of 4000µstrain lies far right of the CDF plot, indicating almost zero (100% safety) probability of failure. On the other hand, the CDF plots for the performance function indicate a failure probability of the miniscrew for each variation. Figure 5 represents the values for the probability of failure of the cancellous bone, exceeding the random limit value. Similar to the first analysis at which the limit value is kept constant, smaller variations may lead to smaller failure probabilities. On the other hand, when the uncertainty regarding the young's modulus of the bone increases, the failure probability also takes higher values for the CVs having more than 30% of the variation.

These results demonstrate that reaching a conclusion about the stability of a miniscrew or proposing specific thresholds indicating the stability based on deterministic parameters may not be in accordance with the results obtained from either experimental studies or clinical observations. Therefore, taking into account not only the uncertainties related to parameters affecting the FE-based results but also considering the threshold value as a random variable may give a more accurate assessment of the stability of a miniscrew.

This study utilizes patient-specific modelling of the mandible from a patient's CT. Thus, the FE model represents an anatomical high-fidelity model. On the other hand, while bones can be classified as non-homogeneous, porous and anisotropic tissue, similar to most of the studies in this field, both cortical and cancellous bones are assumed to have linear elastic material properties. However, the main objective of this study was to indicate that uncertainties regarding the parameters used in FE-based analyses may have substantial effects on the judgement about the stability of a miniscrew. Therefore, the remarks made in this study can be considered valid for the case in which the material properties of bones are assumed as anisotropic.

Conclusions

The primary goal of using an FEA is to obtain pre-operative information and provide clinicians with the information so that the success rate of miniscrews can be dramatically increased. Although recent studies in this field utilize deterministic FE analyses to obtain the behaviour of the miniscrew, the current study shows that the uncertainties regarding the parameters that affect the results obtained from FE-based analyses should be used to evaluate the stability of the miniscrew accurately. In addition, the computation of the failure probability of a miniscrew should consider the uncertainty regarding the threshold value for which the FE results are compared. As shown in this study, the analyses in which a constant threshold value is taken into account indicate no failure, whereas the probabilistic analysis in which the random effect of the threshold value is considered yields a failure probability for the miniscrew [20].

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Author contributions

Irfan Kaymaz: Conceptualization, Writing - Original Draft, Project administration, Funding acquisition,
Fatih Alibeyoglu: Software, Validation, Formal analysis, Visualization Data Curation
Ilhan Metin Dagsuyu: Conceptualization, Methodology, Resources

Disclosure statement

No potential conflict of interest was reported by the authors.

Ethical approval

This study was approved by the Ethics Committee of the Faculty of Medicine of the Atatürk University(Turkey)(no: B.30.2.ATA.0.01.00/91)

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