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The effect of nickel-titanium rotary systems on the biomechanical behaviour of mandibular first molars with curved and straight mesial roots: a finite element analysis study

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Abstract

The objective of the study was to discuss the effect of root canal preparation using files with varying tapers and active cutting parts on stress distribution in mandibular first molars with curved and straight mesial roots via 3-dimensional (3D) finite element analysis (FEA). Mesial root canals of six artificial mandibular molar models were prepared up to ProTaper Universal F2 (size 25/0.08 taper) (Dentsply Sirona Endodontics, Ballaigues, Switzerland), ProTaper Universal F3 (size 30/0.09 taper), FlexMaster (VWD, Munich, Germany) (size 25/0.04 taper), FlexMaster (size 30/0.04 taper), Hero Shaper (Micro-Mega, Besançon, France) (size 25/0.04 taper) and Hero Shaper (size 30/0.04 taper). The 3D models with curved mesial roots were constructed from the micro-computed tomographic images of the six prepared models and also one unprepared artificial model. Subsequently, 3D molar models with straight mesial roots were developed. Occlusal force of 200 N was applied and FEA was performed using the Abaqus software (Abaqus 6.14, ABAQUS Inc., Providence, RI, USA). Maximum Principal Stress (Pmax) values and distributions were calculated. In both curved and straight rooted groups, the highest Pmax stresses were recorded for ProTaper F3 model and the lowest Pmax stresses were recorded for intact molar model, followed by Hero Shaper (size 25/0.04 taper) model. All of the models in straight rooted group exhibited lower Pmax values than their counterparts with curved mesial roots. Curved mesial root anatomy may increase the risk of fracture in mandibular molars compared to straight mesial root anatomy. Nickel-titanium rotary systems with a short active cutting part and a low degree of taper may be advantageous in terms of reducing fracture risk in mesial roots of mandibular molars.

Keywords Finite element analysis, Stress distribution, Mandibular first molar, Mesial root curvature

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Introduction

Vertical root fractures (VRF) have a poor prognosis and often necessitate extraction of the affected tooth [1]. Several factors contribute to the occurrence of VRF, including heavy occlusal loads, iatrogenic dental treatments, and anatomical features [2–4]. Among anatomical factors, original dentine thickness, root canal morphology, external root shape, and the presence of proximal concavity significantly influence stress distribution within the tooth. These inherent characteristics cannot be altered by the clinician [3, 5, 6].

The mesial roots of mandibular molars exhibit a high incidence of root fractures, regardless of endodontic treatment [7–11]. The morphology of the mesial root is a crucial determinant of fracture susceptibility, with flat and mesiodistally narrow roots being more prone to fracture [11, 12].

Root canal preparation plays a direct role in determining the remaining dentine thickness and the shape of the root canal, thereby affecting susceptibility to VRF. The use of different rotary systems in preparation can influence stress distribution within roots [13–15]. Notably, rotary systems with larger tapers may increase fracture susceptibility [15].

Finite element analysis (FEA) is a widely used method for assessing stress distribution in dental structures under various conditions [16, 17]. Several FEA studies have utilized 3D-printed models to compare the effects of different rotary systems [13, 15]. MM.Tooth is a commercially available replica of a natural mandibular molar, fabricated from a material similar to dentine. The use of such models allows for standardized root canal configurations, facilitating reliable comparisons.

A limited number of studies have evaluated stress distribution in curved roots [18, 19]. A previous study investigating stress distribution in mandibular second premolars with varying degrees of root curvature reported that curved root models exhibited slightly higher tensile stress levels than straight root models [18]. However, this study focused on the impact of different post systems, and all models had identical root canal preparations. Similarly, Cheng et al. analyzed the biomechanical behavior of mandibular incisors with curved root canals prepared using different techniques, but root canal curvature was not considered as a variable [19].

Therefore, this study aims to evaluate the effects of rotary systems with varying tapers and active cutting parts on stress distribution in mandibular first molars with curved and straight mesial roots using three-dimensional (3D) finite element analysis. The hypotheses tested in this study are as follows: (1) mesial canal preparation with different rotary systems does not influence stress magnitude and distribution within mandibular molars under occlusal loading, and (2) the degree of mesial root curvature does not affect stress magnitude and distribution within mandibular molars under occlusal loading.

Materials and methods

Selection of artificial tooth model

MM.Tooth models (Micro-Mega, Besançon, France) with material properties similar to natural dentine were used for simulation. These artificial tooth models are precise replicas of natural mandibular molars, fabricated using 3D printing technology based on micro-computed tomography data. Seven identical MM.Tooth mandibular molar models, each containing three canals (mesiolingual, mesiobuccal, and distal), were selected. Mesial canals had a severe curvature (50° angle) and a Type II Vertucci configuration [20, 21]. The working lengths were measured as 23 mm for the mesiobuccal canal and 23.5 mm for the mesiolingual canal. Mesial canals of six models were prepared with different rotary systems, while one model remained intact as a control. To avoid excessive cervical enlargement, coronal enlargement files were not used, and the final taper of each system was preserved.

Root canal preparation protocol

Root canals were instrumented with an X-Smart endodontic motor (Dentsply Sirona Endodontics, Ballaigues, Switzerland) following manufacturer-recommended rpm and torque settings. The applied file sequences are summarized in Table 1.

The distal canal remained unprepared. To ensure consistency, all procedures were performed by a single operator (Y.C.). Irrigation was performed using 2 mL sodium

Table 1 The applied file sequences for each model

Model	Rotary System	File Sequence	Active Cutting Part	Working Length (WL)
Model 1	ProTaper Universal (Dentsply Sirona)	S1 (17/.02), S2 (20/.04), F1 (20/.07), F2 (25/.08)	16 mm	Up to WL
Model 2	ProTaper Universal (Dentsply Sirona)	S1 (17/.02), S2 (20/.04), F1 (20/.07), F2 (25/.08), F3 (30/.09)	16 mm	Up to WL
Model 3	Hero Shaper (Micro-Mega)	20/.04, 25/.04	12 mm	Up to WL
Model 4	Hero Shaper (Micro-Mega)	20/.04, 25/.04, 30/.04	12 mm	Up to WL
Model 5	FlexMaster (VDW)	20/.04, 25/.04	16 mm	Up to WL
Model 6	FlexMaster (VDW)	20/.04, 25/.04, 30/.04	16 mm	Up to WL
Model 7	Unprepared intact mandibular molar	-	-	-

hypochlorite per canal, with a final rinse of 3 mL sodium hypochlorite to prevent debris accumulation.

Finite element model construction

Models with curved mesial roots

Curved Mesial Root Models

All models were scanned using a micro-CT device (Skyscan 1174, Skyscan, Kontich, Belgium). Data was reconstructed with NRecon (version 1.6.9.4, Skyscan, Kontich, Belgium) and saved in BMP format. Using Mimics software (Materialise, Leuven, Belgium, version 10.01), 3D models were generated. Constructed prepared models had mesiobuccal canal length of 14 mm and mesiolingual canal length of 16 mm. The root canal curvature of the mesial canals was severely curved (50° angle) according to Schneide's method [21].

Straight mesial root models

Curved-root models were digitally modified to reduce mesial root curvature from 50° to 5°, keeping all other anatomical features identical (root length, dentine thickness, and bifurcation position). This standardization ensured valid comparisons between straight and curved-root configurations.

FEA model construction and boundary conditions

In accordance with clinical practice, the root canals of prepared models were simulated as filled with gutta-percha from the apical foramen up to 1 mm apical of cemento-enamel junction. The remaining access cavity was designed as filled with glass-ionomer cement and composite resin. Since there is no structure to mimic enamel and cement in the MM.Tooth models, enamel contours were formed according to common natural mandibular molar tooth anatomy [22]. Cementum was not modeled, as its influence on FEA results is minimal. The periodontal ligament was simulated as a soft, incompressible material (250 µm thickness) terminating 1.5 mm apically from the cemento-enamel junction. Alveolar bone structure was modeled around the periodontal ligament in the form of mandibular bone anatomy. Cortical bone thickness was simulated as 1 mm.

FEA models were meshed using ABAQUS 6.14 software (Hibbitt, Karlsson & Sorensen, Inc., Pawtucket, RI, USA). Tetrahedral elements were applied, with mesh sizes of ≤ 0.5 mm in high-stress regions. Each model contained approximately 1,800,000 elements.

Mechanical properties and loading conditions

All tissues and materials in the present study were considered homogeneous, isotropic and linearly elastic. The interfaces between the different restorative materials and dentin were considered to be completely bonded. Elastic modulus values and Poisson's ratio values of the tissues

Table 2 Mechanical properties of materials applied in the finite element analysis

	Elastic Modulus (GPa)	Poisson's Ratio
Enamel (Belli et al.2016) [16]	41	0.31
Dentine (Belli et al.2016) [16]	18.6	0.31
Pulp (Belli et al. 2016) [16]	0.003	0.45
Periodontal ligament (Belli et al. 2016) [16]	0.0000689	0.45
Gutta-percha (Belli et al.2016) [16]	0.14	0.45
RMGIC (Celik Koycu et al. 2016) [17]	10.6	0.30
Composite resin (Ren et al. 2010). [25]	16.4	0.28
Cancellous bone (Ren et al.2010). [25]	1.37	0.30
Cortical bone (Ren et al. 2010). [25]	13.7	0.30

and materials were assigned as specified in the literature (Table 2). The models were constrained at the lower base of the supporting mandibular bone. Oblique loading (135° angle) and vertical loading forces (200 N) were applied to five occlusal contact points (central fossa, distal marginal ridge, mesiobuccal cusp, distobuccal cusp, and distal surface).

Stress analysis

Static linear FEA was conducted using ABAQUS 6.14, and Maximum Principal Stress (PMax) values were analyzed. The volume of elements with PMax > 11 MPa was calculated for oblique loading scenarios. To improve visualization, numerical data were converted into color-coded graphics, where PMax stress values were represented as positive values. High-stress areas were highlighted in red and yellow, making it easier to interpret the stress distribution within the models.

Results

Oblique loading

In both root configurations, the Maximum Principal Stress (PMax) was concentrated on the lingual cervical external root surface of the mesial roots (Figs. 1 and 2). In straight-rooted models, PMax stresses extended towards the middle portion of the mesial roots, while in curved-rooted models, stress was more localized and concentrated (Fig. 2, Table 3). The volume of high-stress areas was generally larger in straight-rooted models compared to curved-rooted models (Figs. 2 and 3), indicating a more evenly distributed load in the former.

PMax stress magnitudes were higher in curved-rooted models than in their straight-rooted counterparts (Table 2). Additionally, models with larger apical dimensions (0.30 mm) exhibited greater volumes of high-stress areas in both root configurations (Fig. 4).

In all rotary system models, those with a 0.25 mm apical size demonstrated lower stress values than those with a 0.30 mm apical size, suggesting that a more conservative

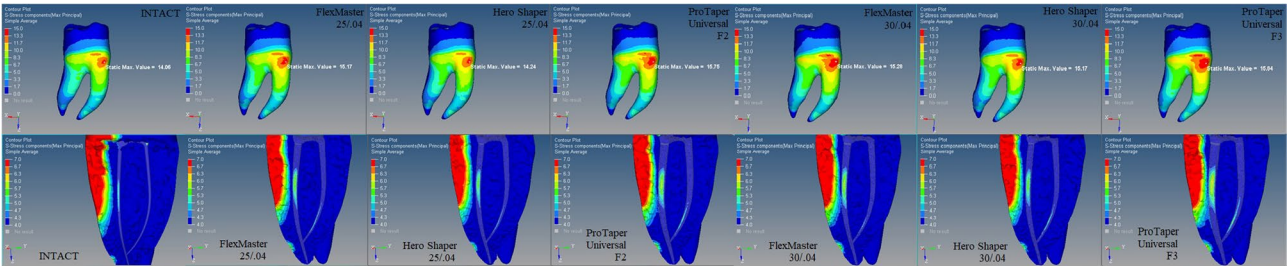


Fig. 1 PMax stress distributions in mandibular molars with curved mesial roots under oblique loading. Upper row: lingual aspect view; Lower row: buccolingual section of the mesial root

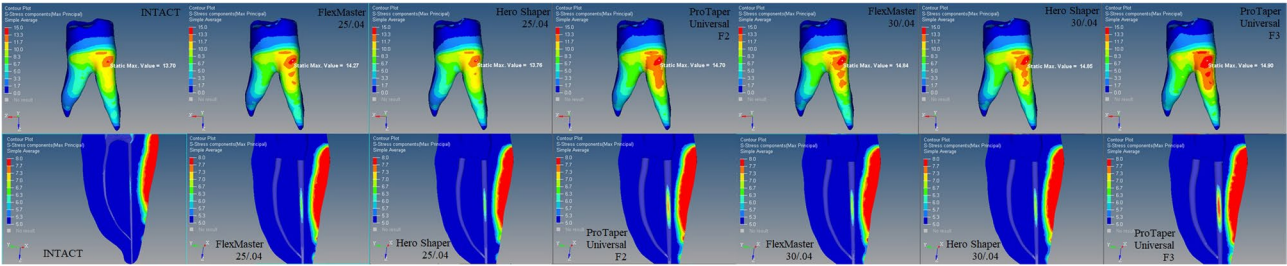


Fig. 2 PMax stress distributions in mandibular molars with straight mesial roots under oblique loading. Upper row: lingual aspect view; Lower row: buccolingual section of the mesial root

Table 3 Highest PMax values calculated in curved and straight-rooted models

	Oblique Loading		Vertical Loading	
	Curved-Rooted Model Pmax Value	Straight-Rooted Model Pmax Value	Curved-Rooted Model Pmax Value	Straight-Rooted Model Pmax Value
Intact	14.06	13.70	7.58	5.92
FlexMaster 25/04	15.17	14.27	8.20	8.41
FlexMaster 30/04	15.28	14.84	8.48	8.80
HeroShaper 25/04	14.24	13.76	8.02	7.73
HeroShaper 30/04	15.17	14.85	8.31	7.77
ProTaper F2 25/08	15.75	14.70	8.51	8.81
ProTaper F3 30/09	15.84	14.90	8.98	9.12

preparation may reduce stress levels (Table 3). Buccolingual plane images revealed that PMax stresses extended deeper into the ProTaper Universal F3 model (Model 2) compared to other models (Fig. 1).

Vertical loading

Under vertical loading, PMax stresses were localized in the bifurcation area for both root configurations (Fig. 3). The stress distribution patterns were comparable in both

straight and curved mesial roots, indicating that mesial root curvature has a lesser impact under purely vertical forces compared to oblique forces.

As in the oblique loading scenario, the intact model (Model 7) exhibited the lowest PMax values, while the ProTaper Universal F3 model (Model 2) displayed the highest PMax values in both straight and curved roots (Table 3). The Hero Shaper 25/0.04 model (Model 3) had the lowest PMax values among the prepared models, with stress distribution and magnitudes closely resembling those of the intact model (Model 7) (Table 3).

Discussion

Finite element analysis (FEA) has been widely utilized to evaluate stress distribution in dental structures, particularly in endodontics [15, 16, 23]. This computational method eliminates variables associated with anatomical and physical differences, enabling precise assessment of specific biomechanical factors [5]. Unlike in vitro and clinical studies, FEA allows for the visualization of both peak stress values and overall stress distribution. However, it has inherent limitations, such as the assumption that all applied materials are isotropic and homogeneous, which does not fully reflect the complexity of actual anatomical structures. Additionally, this study applied static linear analysis, whereas fatigue-induced fractures are more commonly responsible for cracks in endodontically treated teeth [24]. Furthermore, the interfaces between different restorative materials were assumed to be fully

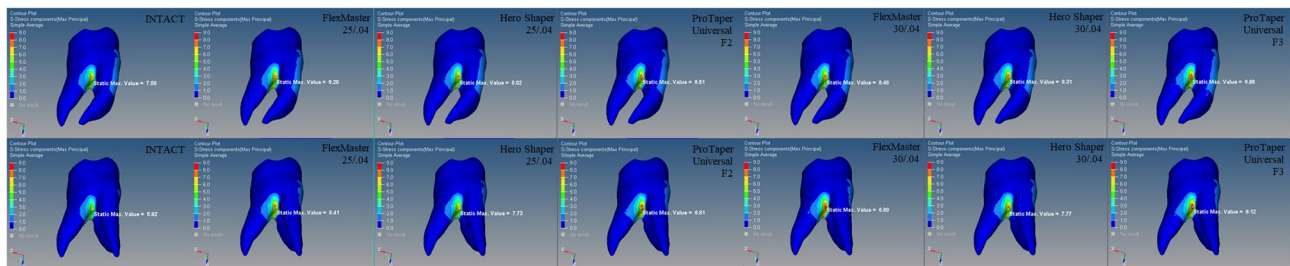


Fig. 3 PMax stress distributions in mandibular molars with curved and straight mesial roots under vertical loading. Upper row: curved mesial root; Lower row: straight mesial root

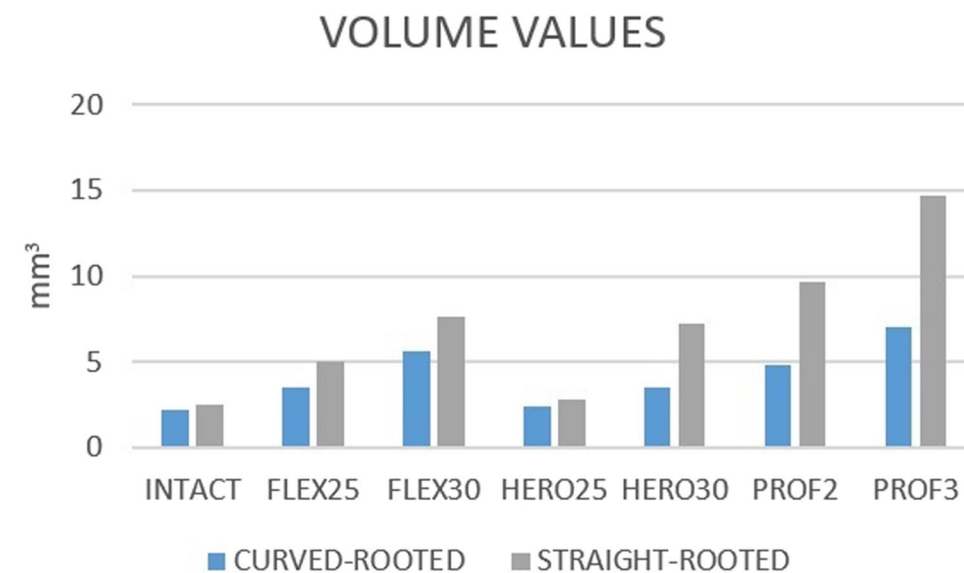


Fig. 4 Volume of elements reaching 11 MPa and above under oblique loading in mandibular molars with curved and straight mesial root

bonded, despite potential variations in material interactions. While frictional forces between dentin and restorative materials were disregarded due to negligible relative displacements, this remains a simplification frequently employed in FEA studies.

This study utilized standard MM.Tooth models, which are 3D-printed replicas of natural mandibular molars based on micro-computed tomography (micro-CT) data. Extracted human molars were not used due to challenges in standardizing root canal anatomy and external morphology. The MM.Tooth models closely mimic dentine's cutting properties, providing a reliable and accurate preparation method. These models have a severely curved mesial root with a 50° curvature [21], which was virtually modified to 5° to compare the effects of curved and straight mesial roots. While alternative approaches, such as generating FEA models from micro-CT images of separate artificial straight-root models, could have been used, this method would not have ensured identical dentin thickness, concavity, and structural integrity across models. Thus, virtual modification was considered the

most appropriate approach. However, a limitation of this method is the potential variation in dentin removal patterns due to differing pressure dynamics in curved and straight canals during preparation.

Since MM.Tooth models lack enamel and cementum, enamel boundaries were virtually constructed following established literature [22]. Root cementum was not modeled, as it has a negligible impact on FEA results [25]. Dental structures exhibit high compressive strength but are less resistant to tensile forces [5]. Therefore, maximum principal stress (PMax) values, which indicate tensile stresses and predict potential fracture lines, were analyzed in this study.

A 200 N occlusal force was applied at five contact points in both vertical and oblique directions to simulate masticatory forces [17]. While the stress values in this study remained below the reported ultimate tensile strength of dentin (40–100 MPa), it is important to note that higher chewing forces could proportionally increase stress levels. Additionally, structural defects, cracks, and root canal irregularities in dentin can significantly alter

tensile strength [5]. Previous studies have reported that oblique forces generate higher stress concentrations and have more detrimental effects on teeth than vertical forces [14, 26]. Consistent with these findings, our study demonstrated that oblique forces induced higher PMax stresses than vertical forces.

The effects of different file designs and mesial root curvature on stress distribution in mandibular molars were evaluated. Coronal enlargement files were deliberately excluded from the preparation protocol, as their use would have altered the final root canal taper and obscured the effects of files with 12 mm active cutting portions. Instead, a conservative preparation approach was emphasized using Hero Shaper files (0.04 taper, 12 mm active cutting portion).

The ProTaper Universal F3 file may not be ideal for severely curved canals due to its large taper, which increases the risk of procedural errors and instrument fracture [27–30]. In this study, ProTaper Universal F3 was included to represent excessive iatrogenic enlargement of mesial canals, providing insights into the impact of aggressive preparation techniques.

The results demonstrated that mesial root curvature and rotary system design significantly influence stress distribution within mandibular molars. Therefore, both study hypotheses were rejected. The distribution of stresses, the volume of high-stress areas, and the magnitude of stress were comparable between intact teeth and the Hero Shaper 25/0.04 models, while the ProTaper Universal F3 model exhibited the highest stress values. These findings correlate with the remaining cervical dentine thickness, as dentine loss in the cervical region increases fracture susceptibility. The Hero Shaper 25/0.04 file provided a conservative preparation, minimizing cervical dentine loss, while the ProTaper Universal system, with its greater taper and 16 mm active cutting portion, led to increased stress levels.

Consistent with our findings, a previous study analyzing the effects of different file systems on stress distribution in maxillary two-rooted premolars reported that the Hero Shaper system produced stress values and distribution patterns similar to those of intact teeth, whereas the ProTaper Universal group exhibited the highest stresses [14]. The same study calculated the highest stresses in the ProTaper Universal group similar to the present study [14]. Several studies have shown that high-taper files result in greater dentine loss in the cervical third of the root, increasing fracture susceptibility [6, 14, 15]. Similarly, an FEA study comparing mandibular molars with 0.04, 0.10, and 0.12 taper canal preparations concluded that smaller tapers reduce fracture risk [31].

In this study, for each file system, the 0.30 mm apical diameter preparation generated higher stress values

than the 0.25 mm preparation. This is likely due to the increased coronal diameter associated with larger apical sizes. A previous FEA study comparing mandibular molars treated with TRUShape 0.20/0.30 and Vortex 0.20/0.30 files also reported higher stresses in models prepared with 0.30 mm apical diameters compared to 0.20 mm [13].

Limited studies have examined the impact of root curvature on stress distribution [18, 19]. This study compared mandibular molars with straight (5°) and severely curved (50°) mesial roots, demonstrating that higher curvature was associated with increased stress concentrations. In contrast, straight-rooted models exhibited more uniform stress distribution across a larger root surface area, which may help prevent localized stress accumulation. Similar results were reported in a recent FEA study on mandibular premolars, where increasing root curvature corresponded with greater stress concentration areas [18]. However, the previous study primarily focused on post types and coronal restorations, whereas the present study incorporated root canal preparation with varying tapers.

Conclusions

Severely curved mesial root anatomy increases fracture risk in mandibular molars compared to straight mesial roots. Nickel-titanium rotary systems with shorter active cutting portions and lower tapers may be advantageous in reducing stress accumulation, thereby minimizing fracture susceptibility in mesial roots of mandibular molars. These findings highlight the importance of conservative preparation techniques in endodontic treatment.

Abbreviations

FEA	Finite element analysis
PMax	Maximum principal stress
3D	Three-dimensional
VRF	Vertical root fracture
CT	Computed tomography
µm	Micrometer
MPa	Megapascal
WL	Working length

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Not applicable.

Authors' contributions

YC designed the study, performed the root canal preparations, constructed the artificial tooth models, and conducted the initial data analysis. SAÖ contributed to the study design, supervised the experimental procedures, interpreted the results, and was responsible for manuscript writing and revision. AS provided methodological guidance, supervised the research process, and critically reviewed the manuscript. MO constructed the finite element models, performed the simulations, and contributed to data interpretation. All authors read and approved the final manuscript.

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Data availability

All data generated or analyzed during this study are included in this published article.

Declarations**Ethics approval and consent to participate**

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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