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Evaluation of stress distribution in restorations of maxillary central incisor with post-traumatic enamel-dentin fracture using two different techniques: A micro-computed tomography study

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Abstract

Aim: The aim of this study is to investigate the stress distribution created by two restorative techniques, adhesive reattachment of the fractured fragment and direct composite restoration, used in the treatment of a maxillary central incisor with enamel-dentin fracture. The analysis is conducted using the finite element stress analysis method on a three-dimensional (3D) model prepared based on micro-computed tomography data, following the application of different adhesive procedures on fractured teeth.

Methodology: The avulsed left maxillary central incisor was scanned using a micro-computed tomography device. The obtained data was transferred to a computer and used for 3D modeling. In the models, a fracture line was created obliquely at a 45˚ angle, 3 mm away from the mesial surface towards the distoincisal corner of the tooth. Six restorations were planned on this model: three direct composite restorations and three adhesives, reattachments followed by composite application. The models for the adhesive reattachment method included: (1) internal dentin groove, (2) palatal composite laminate veneer, and (3) double palatal retentive groove. The models for the composite restoration technique included: (1) composite laminate veneer, (2) direct composite restoration following enamel beveling, and (3) composite application after double palatal groove preparation. Upon completion of the restorations, a 100-N force was applied from the palatal direction using the finite element stress analysis method. The results were analyzed to examine the amount and distribution of stress on the restorations and the tooth.

Results: In all models, the highest stress values within tooth structures were observed in the enamel. The lowest stress value in the enamel layer was seen in model R-1, whereas the highest stress value was observed in model K-2. For direct composite restorations, the stresses on enamel, dentin, and restoration were relatively similar in each model, with no significant differences noted among these values. Among all applied composite restorations, the lowest stress value was observed in model R-3. When analyzing the stresses generated at the tooth-restoration and tooth-fractured fragment interface of the six models, the lowest stress in the enamel was observed in models R-1 and K-3, while the highest stress was seen in model R-3.

Conclusion: According to the data obtained from the models, the shape of the restoration applied on the tooth, the technique used, and the location of the restoration affect the amount and distribution of stress accumulated in the tooth and restoration. However, the stress analysis results are not sufficient to evaluate the clinical success of restorations. There is a need for further studies utilizing different techniques to support the models used.

Keywords: Reattachment technique, stress distribution, finite element analysis, micro-computed tomography, direct composite restoration, enamel dentin fracture

Introduction

Maxillary central incisors are the most commonly traumatized teeth within the dental arch (1). The most frequently observed type of trauma in these teeth is enamel-dentin fractures resulting from hard tissue injuries. Damage or loss of anterior teeth in children not only leads to psychological and social problems but also adversely affects speech and feeding functions (2). Achieving ideal aesthetics, fracture resistance, and durability during the restoration of anterior teeth with enamel-dentin fractures can be challenging. Therefore, the treatment of traumatically injured anterior teeth is particularly important. Restorations for enamel-dentin fractures are expected to provide sufficient aesthetics and resistance, ensuring long-lasting durability (3,4).

With the discovery of adhesion to enamel and the development of adhesive systems, invasive procedures, such as acrylic crowns and full-coverage restorations, have given way to more conservative techniques, such as reattachment and direct composite restoration in the treatment of fractured teeth (5–9). To maximize the benefit of adhesion to enamel in these techniques, various retentive procedures that can be applied to both the fractured tooth and the remaining tooth structure have been recommended (6,10–12). For the reattachment technique, these procedures include an internal dentin groove, palatal retentive grooves, palatal laminate veneer, overcontour restoration, chamfer preparation, and others. For direct composite restoration, applicable procedures include direct composite laminate veneer, buccal or circumferential chamfer preparation, enamel beveling, palatal or buccal retentive grooves, and more. The selection of which technique to use in restoration planning is influenced by several factors, including the presence of the fractured piece, compatibility with the tooth, the plane of fracture, and the distance to the pulp. Various studies are being conducted on the durability of these techniques against intraoral biomechanical forces.

It is not yet possible to fully define intraoral biomechanical forces using in vitro techniques. Therefore, different restorative techniques must be investigated and validated using various laboratory methods. In many studies examining different restorations and retentive procedures used in the treatment of enamel-dentin fractures, fracture strength has been measured using a universal testing machine. In a limited number of studies, stress analysis measurement methods have been utilized (10, 11, 13–19). Although several stress analysis measurement methods are currently available, the method that provides results closest to reality is the three-dimensional finite element stress analysis (FESA) method, which can mimic chewing forces and the oral environment. After a three-dimensional scan of the desired object is obtained with this method, the data are transferred to a computer, and various programs are used to obtain the exact real-world dimensions of sections and shapes of the desired thickness. Forces of predetermined magnitudes are applied to the object, and the stresses occurring in the structures related to the biomechanics of the used objects can be determined visually and numerically (20).

The aim of this study is to measure the amount and distribution of stress exhibited under palatal forces by the reattachment technique and direct composite restoration technique on central maxillary incisors using three different retentive procedures.

Materials and Methods

This study was approved by the local ethics committee of the Dicle University Faculty of Dentistry (decision number: 2021-13).

A non-adult patient's single-rooted and single-canal maxillary central incisor was used in the study.The tooth for the model of the maxillary incisor was scanned using a high-resolution SkyScan 1172 μCT (Bruker, Kontich, Belgium) with an isotropic voxel size of 13.68 μm. A total of 1,773 slices were obtained from scans completed twice at 180° rotation intervals and a step size of 0.9° (Fig. 1). The tomographic data were reconstructed using a slice thickness of 0.1 mm. The reconstructed tomographic data in the DICOM (.dcm) format were imported into the 3D-Slicer software (V4.10.2; https://www.slicer.org/). The micro-CT data in the DICOM format were segmented based on appropriate Hounsfield values in the 3DSlicer software, transforming it into a three-dimensional model. Reverse engineering and three-dimensional CAD activities were performed using ALTAIR Evolve software to prepare solid models for analysis and to create an optimized mesh using ALTAIR Hypermesh software. The solution of the finite element models was carried out using a Nastran-based ALTAIR Optistruct (ALTAIR, Troy, MI) implicit solver.

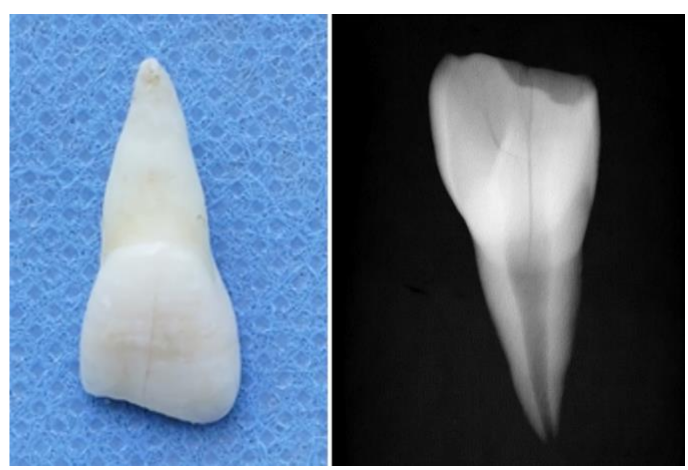

Figure 1. Central maxillary tooth and periapical X-ray image

Trabecular bone was obtained with reference to the inner surface of the three-dimensional maxillary cortical bone. Crown, dentin, and pulp models were derived from the tomographic data via segmentation. A 0.2 mm thick periodontal ligament model was created with reference to the outer surface of the dentin model (21–23). An adhesive bond thickness of 50 microns was set for all models (24, 25). All the prepared models were positioned accurately in three-dimensional space and finalized using modeling in the ALTAIR Evolve software. For models R-1, R-2, and R-3, a total of 318,726, 324,497, 349,766 nodes and 1,223,639, 1,243,665, 1,334,914 elements were used, respectively. For models K-1, K-2, and K-3, a total of 274,377, 310,145, 313,575 nodes and 1,084,657, 1,191,799, 1,209,836 elements were utilized, respectively.

Clinical Scenarios and Restoration Options

A 3 mm oblique fracture line was created from the distal corner to the mesial edge of a centrally obtained dental model. Six clinical scenarios were conducted on the resulting fractured dental model. In the first three scenarios, the fractured tooth fragment was used (reattachment), while in the remaining three scenarios, direct composite restoration techniques were applied without using the fractured tooth fragment. The models were as follows (Fig. 2):

R-1: Following the reattachment of the fractured fragment, a 0.5 mm abrasion from the palatal surface was made to restore this area using a direct composite laminate veneer.

R-2: After reattaching the fractured fragment, two palatal retentive grooves were prepared at depths of 1 mm, widths of 1 mm, and lengths of 4 mm at the enamel level to restore these areas with composite.

R-3: Before bonding the remaining tooth structure, the inner dentin recesses were prepared to be 1 mm wide and 1 mm deep and to extend along the dentin on the fractured fragment and remaining tooth structure. These areas are filled with composite after preparations and performing the reattachment process.

K-1: Perform beveling on the enamel tissue of the remaining tooth structure with a width of 2 mm to restore the tooth with direct composite.

K-2: Perform a 0.5 mm depth abrasion for laminate veneer at a distance of 1 mm from the enamel cement junction on the vestibular surface of the tooth and restore the tooth with direct composite laminate veneer.

K-3: Prepare a palatal vertical retentive groove of 1 mm wide, 1 mm deep, and 2 mm long from the palatal enamel surface of the remaining tooth structure to restore the entire tooth with direct composite.

The Young's modulus and Poisson's ratio, which define the physical characteristics of the structure, are shown in Table 1. All materials are considered homogeneous, linear, and isotropic.

Determination of Contact Surfaces in Models

All modeled materials and anatomical interfaces were assumed to be fully/tightly bonded together.

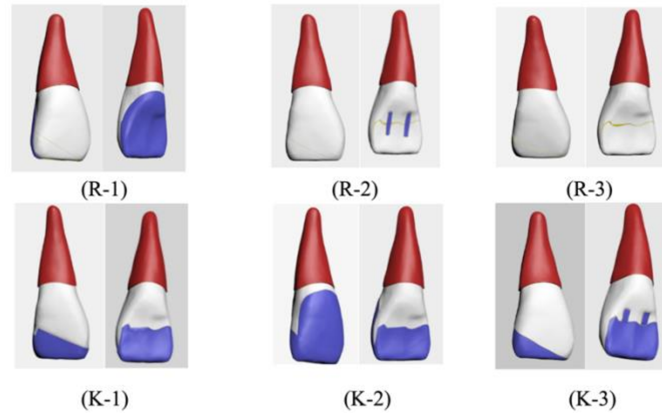

Figure 2. **(R-1)** Palatinal laminate application after reattachment, **(R-2)** Double vertical groove application after reattachment, **(R-3)** Reattachment application after internal dentin groove, **(K-1)** Direct composite application after 2 mm beveling, **(K-2)** Laminate veneer application from the buccal surface with direct composite, **(K-3)** Direct composite application after double palatinal vertical groove.

Loading and Stress Analysis

To simulate the original occlusion, the models were limited by a force of 100 N applied with a steel sphere simulation of 4 mm in diameter on the cusp on the palatal surface of the crowns of the models at a 45° angle from the long axis of the tooth in the palatal direction (Fig. 3) (18, 19, 26–30).

Qualitative stress distribution analyses were recorded in this study using the von Mises criteria. The computed numerical data obtained from each model were transformed into color images. The highest von Mises stress values were recorded for all structures.

Table 1. Modulus of elasticity and Poisson's ratios of materials

Material	Elastic Module [MPa]	Poisson Ratio	References
Composite Resin	24.494	0.31	(31-33)
Cortical Bone	13.7	0.3	(34)
Trabecular Bone	1.37	0.3	(34)
Enamel	84.1	0.33	(23,35-37)
PDL	0.0689	0.45	(38-40)
Adhesive Resin	8.430	0.31	(31,32)
Dentin	18.6	0.31	(38-41)
Pulp	0.003	0.45	(41)
Foodstuff (steel)	200	0.3	(30)

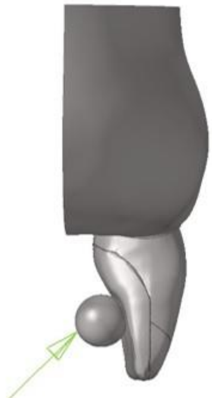

Figure 3. Direction of application of force and the steel sphere used.

Results

The maximum von Mises stress values are indicated in Tables 2 and 3. The application of palatal force resulted in the highest stress values at the enamel in all models (Fig. 4-6). The lowest stress value in the enamel layer was observed in model R-1, while the highest stress value was seen in model K-2. In model R-1, the palatal composite laminate veneer restoration, located on the palatal enamel, served the purpose of accommodating forces on the tooth, resulting in the least stress in the enamel tissue and the highest stress in the composite restoration in this model. In the K-2 restoration, the laminate veneer restoration located on the buccal surface of the tooth did not provide additional support against forces coming from the palatal direction.

In direct composite restorations, the stress values occurring on the enamel, dentin, and restoration layers in the models were similar for each model, with no significant differences observed among these values. The lowest stress value among all applied composite restorations was observed in model R-3. This can be attributed to the composite restoration being located in the inner dentin cavity and therefore not directly exposed to force.

When examining the stresses created at the tooth-restoration and tooth-fracture fragment interface in the six models, it was observed that the lowest stress in the enamel occurred in R-1 and K-3, while the highest stress was in R-3.

In all models, the stress concentration on the buccal surface of the root dentin was denser than that on the palatal root dentin, and the stress concentration on the distal root surface was denser compared to the mesial root surface.

Table 2. Maximum von Mises stress values occurring in the tooth structures and restorations after force application

	Enamel	Dentin	Composite	Dentin Broken Fragment	Enamel Broken Fragment
R1	5 815E+01	2 375E+01	8 869E+01	8 828E+00	2 320E+01
R2	1 020E+02	2 185E+01	1 589E+01	5 964E+00	5 606E+01
R3	1 150E+02	1 933E+01	8 578E+00	5 995E+00	4 579E+01
K1	1237E+02	1988E+01	3496E+01		
K2	1266E+02	1902E+01	3173E+01		
K3	1272E+02	2001E+01	2525E+01		

Table 3. Maximum von Mises stress values at the interface of the remaining tooth tissue

	Enamel	Dentin
R1	1.173E+01	8.975E+00
R2	1.423E+01	5.156E+00
R3	2.694E+01	5,990E+00
K1	2.196E+01	6.025E+00
K2	2.461E+01	5.872E+00
K3	1.173E+01	6.213E+00

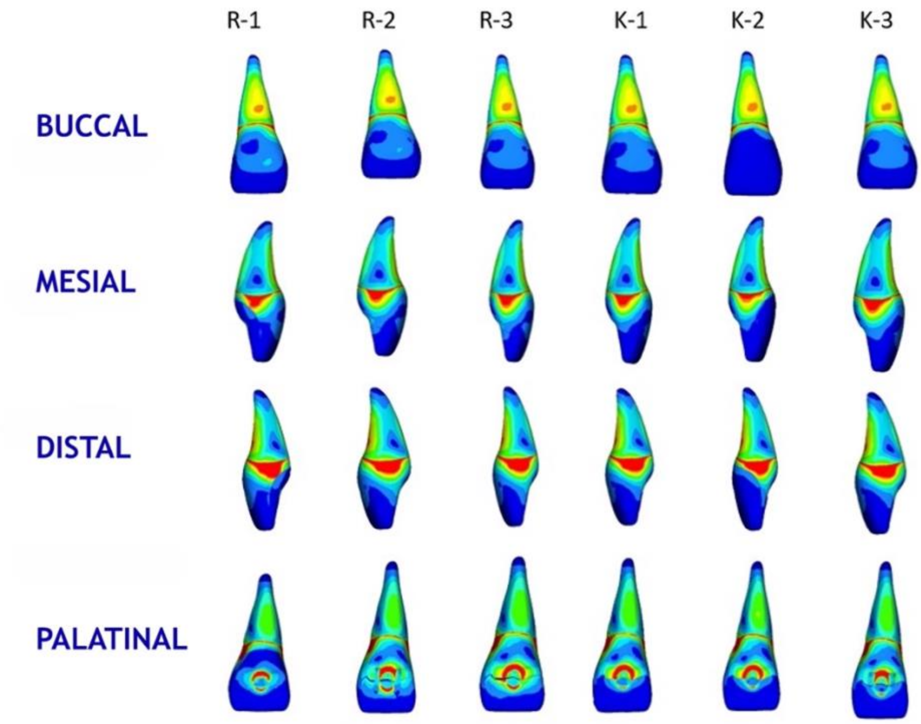

Figure 4. Images of stress distributions of the models under force loading from buccal, mesial, distal and palatinal surfaces.

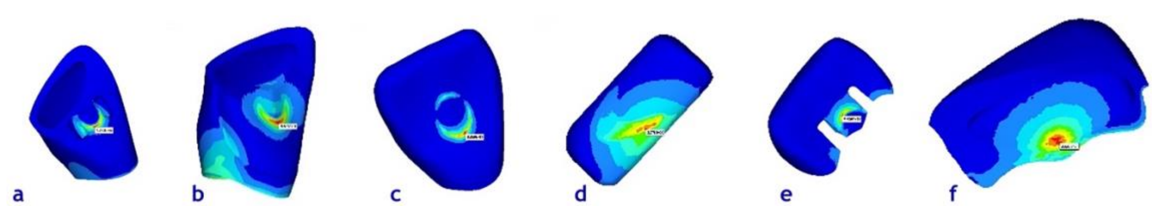

Figure 5. The structures where the highest and lowest stresses occur under force application in dental and composite restorations. (a) the highest stress value occurring in dentin: K-3, (b) the lowest stress value occurring in dentin: R-1, (c) the highest stress value occurring in the composite filling: R-1, (d) the lowest stress value occurring in the composite filling: R-3, (e) the highest stress value occurring in the fractured piece: R-2, (f) the lowest stress value occurring in the fractured piece: R-1.

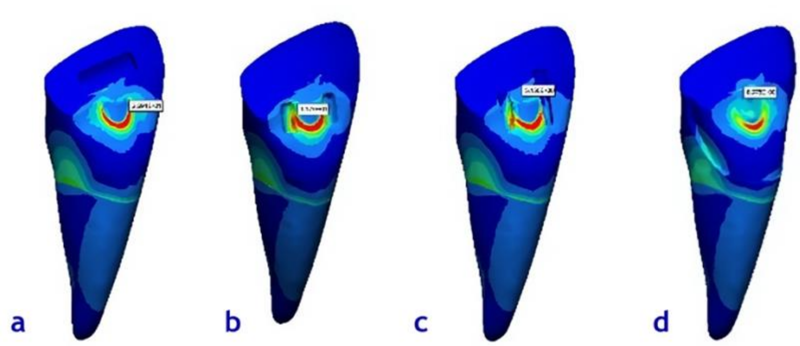

Figure 6. The highest and lowest stresses and their distributions that occur at interfaces: (a) the highest stress occurring in dentin: R-3, (b) the highest stress occurring in dentin: R-1, (c) the lowest stress occurring in dentin: K-3, (d) the lowest stress occurring in dentin: R-2.

Discussion

The purpose of our study was to evaluate the amount and distribution of stress on a fractured permanent maxillary central incisor resulting from different restorative techniques and preparation methods using the FESA method based on micro-tomography data. The results confirm the initial hypothesis that the restoration technique and preparation method both impact the amount and distribution of stress on the tooth.

When examining the stresses at the interface between the restoration and the remaining tooth structures, the lowest von Mises stress value in the enamel tissue was observed in the palatal laminate veneer model; this finding is similar to a study by Guven et al., which examined seven different restorations on a canal-treated fractured maxillary central incisor model (18). Similarly, Arapostathis et al., in a case report, applied composite veneers to the palatal surface of a tooth without preparation or altering the occlusion to strengthen the palatal surface of the tooth after a reattachment procedure; they reported no problems with the restoration at a one-year follow-up (42). Furthermore, Andreasen, using sheep incisors, applied laminate veneers to the buccal surface of tooth models after reattachment procedures; the models to which laminate veneers were applied were found to be more durable than those teeth for which simple reattachment procedures were used, with fracture resistance approaching that of natural teeth (43, 44).

In the current study, in the first model in which palatal composite laminate veneers were applied after reattachment (R-1), the lowest stress value was observed in the enamel of the remaining tooth structure. In model K-2, in which laminate veneers were not used and a direct composite restoration was applied to the buccal surface of the tooth, no significant decrease was observed in either the stress values at the interface of the remaining tooth structure or the stress values in other tissues or regions of the tooth, compared to the other models.

In Zhang et al.'s study on the resin cementation process, they employed both the FESA method and fracture strength testing with four different preparation methods. They compared the results obtained through two different techniques. The researchers utilized four models in their study: direct resin restoration, buccal chamfer, lingual chamfer, and circumferential chamfer. They reported that buccal chamfer and direct resin restoration applications exhibited similar high stress and low fracture resistance, while palatal and circumferential chamfer applications demonstrated high fracture resistance and low interfacial stress. Despite having the same bonded surface area in buccal and lingual chamfer designs, different results were obtained in terms of both fracture resistance and stress accumulation. Zhang et al. concluded in their study that the preparatory procedures on the enamel increased retention; however, they also emphasized that the surface on which the procedure was performed and the direction of force application were crucial in determining stress accumulation and fracture resistance (30). In our study, where the resin cementation procedure was performed with three different preparations in our models (R-1, R-2, R-3), significant differences were observed in the amount and distribution of stress. The restoration of the model (R-1) with the widest bond contact area exhibited the highest stress accumulation, while the enamel tissue of this model showed the lowest stress accumulation.

Xu et al. investigated the effects of different cavity designs on stress distribution and fracture strength in a maxillary central incisor model with oblique dentin fractures using the FESA method and a universal testing machine. Analyzing the forces coming from centric and protrusive occlusions, they reported that the stresses were highest under protrusive occlusion in all models and that the chamfer group exhibited higher stress and higher fracture resistance than the bevel group. The FESA analysis of the bevel group indicated no significant difference in stress accumulation between 1 mm and 2 mm bevels, but a substantial difference was observed in fracture strength testing. In the current study, with a 2 mm bevel model for restoration (K-1), no significant differences were observed in terms of the maximum von Mises stress values or stress distributions compared to the other three composite restoration designs (19). However, according to Xu et al., making a direct inference about the durability of a restoration based solely on stress analysis data can be misleading.

In our study, the maximum von Mises stress values at the interface between tooth-composite and fractured tooth fragments indicated that the lowest stress occurred in the enamel for the R-1 and K3 models. Upon analyzing the maximum stresses occurring in the enamel of the overall tooth structure, it was observed that lower stresses were present for the enamel belonging to the remaining tooth structure in models with reattachment (R-1, R-2, R-3) compared to models with direct composite restoration (K-1, K-2, K-3). Application of force on the teeth revealed higher stress accumulation areas in the buccal cervical region, on the palatal surface of the tooth where the force was applied, and on the buccal surface of the root.

Conclusion

Despite the numerous advantages of the FESA method, one of its limitations is that dental structures actually exhibit anisotropic characteristics while being considered isotropic structures when models are created. Studies have shown that the choice and thickness of the restorative material can impact the amount of stress transmitted to the tooth and surrounding tissues. Therefore, research involving restoration applications of various thicknesses will contribute to the literature. On the other hand, due to differences in geometry and boundary conditions, results obtained from FESA cannot be directly compared numerically with other studies. Results from three-dimensional FESA studies can only be compared in terms of their distribution locations and intensities. The method of obtaining the three-dimensional model, the number of nodes and elements used, the cavity preparation shapes performed, the models created, the materials used, and other factors make our study unique with no similar study available. As a result, our study cannot be directly compared with other SESA studies.

The results obtained have confirmed the hypothesis that the restoration technique used and the preparation shape adopted, which we considered as the initial hypothesis, influence the amount and distribution of stress accumulated on the tooth. Evaluating the success of a restoration solely through stress analysis may not be sufficient, thus necessitating the need for guiding studies on restoration techniques and cavity preparation shapes through various measurement methods among other physical, mechanical, and chemical parameters in both in vivo and in vitro studies.

Disclosures

Ethical Approval: Ethics committee approval was received from the Dicle University Faculty of Dentistry Local Ethics Committee, in accordance the World Medical Association Declaration of Helsinki, with the approval number: 2021-13.

Peer-review: Externally peer-reviewed.

Author Contributions: Conception – Ş.O.A.; Design – Ş.O.A., S.Ç.; Supervision – S.Ç.; Materials – Ş.O.A.; Data Collection and/or Processing – Ş.O.A., Ö.A.; Analysis and/or Interpretation – Ş.O.A.; Literature Review – Ş.O.A., S.Ç.; Writer –Ş.O.A.; Critical Review – S.Ç., Ö.A.

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