Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal 2022, 16(3), 226–233
https://doi.org/10.12913/22998624/149599
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Received: 2022.04.11
Accepted: 2022.05.14
Published: 2022.06.01

Stiffness Analysis of the External Fixation System at Axial Pressure Load

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ABSTRACT

The paper analyzes the stiffness of the Orthofix external fixation system at axial pressure load, applied to the lower leg in case of an unstable fracture. Based on the actual construction of the Orthofix fixator, its 3D model was formed, and then a structural analysis was performed in the CATIA V5 software system. The aim of this paper is to investigate the mechanical properties of Orthofix fixator. FEM analysis of the fixator revealed displacements at characteristic points of the structure and fractures. During the FEM analysis, it is possible to change the load values, all with the aim of obtaining the best possible information about the behavior of the fixator during installation and use by the patient. Based on the results obtained from the FEM analysis, it can be concluded that the Orthofix fixative shows very good stiffness, but also that it can be improved by using newer materials, such as composite or some alloys of titanium and aluminum.

Keywords: external fixation device, stiffness analysis, interfragmentary displacements, principal stresses.

INTRODUCTION

Although external fixation is considered to be a new method in orthopedics and traumatology, it has been gradually applied in various forms in medicine for thousands of years [1]. The modern concept of external fixation begins with Jean-Franacois Malgaigene, who in 1840 constructed an apparatus, called a "metal tip," (pointe metallique), a semicircular shape that extends around the extremity, allowing positioning above any fragment [2]. The first commercial fixator was constructed by Clayten Parkhill in 1897. He was the first to develop a true unilateral fixator called a bone clamp. In this construction, there were two screws connected to a single fragment, and they were connected to each other by a single plate [3]. After Parkhill's fixator, many commercial fixators appear on the market.

Stiffness of the fixation device is defined according to specific type of load: axial load due to pressure force, bending and torsion [4]. Additionally, for the purposes of defining properties of these devices, researchers rely on force transducers [5]. In the context of biomechanical research, great focus is put on analyzing the influential construction parameters on the fixation device stability. These parameters include stiffness, maximum Von Mises stress for zones of interest as well as bearing capacity of the pin-bone connection, as shown in many experimental studies [6,7,8]. In recent period, conducted researches are not only based on experimental investigations, but also on benefits of 3D modeling and numerical analysis. This way, a more complete image and understanding of fixation device behavior is obtained [9, 10, 11].

In order to improve necessary tests and make improvements, researchers seek to develop theoretical background of the fixation thematic based on the principles of structural mechanics [12]. Stiffness of the fixation device is defined according to specific type of load: axial load due to pressure force, bending and torsion [13]. Additionally, for the purposes of defining properties of these devices, researchers rely on force transducers [14].

In the context of biomechanical research, great focus is put on analyzing the influential construction parameters on the fixation device stability. These parameters include stiffness, maximum Von Mises stress for zones of interest as well as bearing capacity of the pin-bone connection, as shown in many experimental studies [15].

In recent period, conducted researches are not only based on experimental investigations, but also on benefits of 3D modeling and numerical analysis. This way, a more complete image and understanding of fixation device behavior is obtained [16]. During 70's and 80's years of the last century and with development of new biomechanical materials like polymers and composites, new research directions are established [17].

Since the invention of fixators, their selection, application and installation has been done on the basis of acquired experience and empirical expressions that have changed and improved over the years. Trying to improve the fixators and find the appropriate fixator for a certain type of fracture, scientists are trying to develop a theoretical analysis of the problem based on the principles of structural mechanics. During the research, the stiffness of the fixator is defined according to the types of loads that prevail in the fracture and the environment of the fracture.

All of the commercial fixation device, which are in use today, have undergone the biomechanical tests before usage. Biomechanical investigation of the Orthofix fixation device was not conducted by the means of the exact estimation of it's stability under the loads. The aim of this work is to investigate the mechanical stability of the Orthofix external fixation system at axial pressure load, applied to the lower leg in case of an unstable fracture. The design parameters that are taken into account for the analysis are: the stiffness of the fixator, the value of the maximum von Mises stresses, as well as the displacements at certain points.

MATERIALS AND METHODS

With the development of technical and natural sciences, new materials appear. These new materials have good characteristics. Titanium and aluminum alloys have found great application in orthopedics and traumatology, while stainless steels are the most widely used [18]. With the Orthofix external fixator, two types of materials are used, namely stainless steel and aluminum alloy (Figure 1).

The parts of the fixator that are painted black are made of aluminum alloy T6 – 7075, while the parts shown in gray are made of austenitic stainless steel marked AISI 304 (Figure 1). The mechanical characteristics of the basic parts of the Orthofix fixator are given in Table 1 [19].

In the process of forming the volume model of Orthofix, the first step is to define, ie model, the fixator components. It is known that the fixator consists of couplings, fixation pins as well as a fixator frame. In the module called Part Design, we create the listed components, and then use Assmebly Desing to combine them into one whole, ie to form a 3D model of Orthofix (Figure 1).

After the 3D fixator model was formed, FEM modeling of the fixator components in the CATIA V5 software package was performed. The components of the analyzed Orthofix fixator were modeled with finite elements of the linear and parabolic tetrahedron type, which at the same time represent the basic solid elements in the CATIA V5 system. Both elements belong to the group of 3D isoparametric elements, ie solids with six edges.

Figure 1. External fixation system "Orthofix"

Table 1. Mechanical

Part name	Standard marks	Standard marks (EN)	Modulus of elasticity E (GPa)	Poisson coefficient υ	Density ρ (kg/m³)	Yield strength σ_V(MPa)
Frame	7075-T6	AlZn5MgCu	71.7	0.33	2810	460
Couplings	7075-T6	AlZn5MgCu	71.7	0.33	2810	460
Spherical joints	AISI 304	EN 58E	193	0.29	7900	205
Couplings screws	AISI 304	EN 58E	193	0.29	7900	205
Half pins	1.4441	X_2CrNiMo18	196.4	0.3	8000	800

The Generative Structural Analysis module defines the characteristics of the orthotropic material that will be used for the analysis. The mechanical properties of bone models are given in Table 2 [20].

After the discretization of the Orthofix fixator with finite elements, the connections between the fixator components are defined. he first step in defining a connection is to join the parts in *Assembly Design*, which is not enough for analysis. In addition to connecting the parts, ie forming the assembly, it is necessary to define the type of connection (Figure 2).

After defining the connections, the supports on the Orthofix fixator model are defined, which alsorepresent the limitations on the model (Figure 3).

After defining the constraint, the load is defined on the Orthofix fixator model. Surface load is a load in the form of a force distributed over a defined geometry. The intensity of the load depends on the geometric area in which the force is located, as well as on the type of surface on which it acts. In the fixator analysis, the force is defined using the Force Density function and is entered in the calculation in Newtons (N). After defining the value of the load, the direction of action of the force and the area of action (point, line, surface) are selected. The formed loads are transformed by nodes, giving the possibility of insight into the value of the force in the nodes. In this case, the axial force acts on the segment of the bone model and transforms over the entire surface. (Figure 4).

Table 2. Mechanical properties of bone models

Property	Value
Longitudinal modulus of elasticity	22900 MPa
Tangential modulus of elasticity	10500MPa
Normal modulus of elasticity	14200 MPa
Poisson coefficient in XY plane	0.29
Poisson coefficient in XZ plane	0.19
Poisson coefficient in YZ plane	0.31
Shear modulus in XY plane	6480 MPa
Shear modulus in XZ plane	6000 MPa
Shear modulus in YZ plane	3700 MPa
Density	1850 kg/m³

After the FEM modeling of the fixer components in the CATIA V5 software package, a structural analysis is performed on a given load. During the axial pressure load test, the axial force is defined so that its area of action is the upper part of the bone segment model, ie the action of the upper part of the human body is simulated. The value of the maximum axial pressure load during FEM analysis is 600 N. The value of the load of 600 N was determined based on the recommendations of orthopedists from clinical practice, and guided by research by other authors in this field [21, 22, 23]

Biomechanical studies on external fixation mostly study only the overall stiffness characteristics of different types of fixators and configurations. Here, in addition to the values of the stiffness of the structural design of the Orthofix fixator, the stiffness of the fracture was also analyzed. The stiffness of the clamp structure according to the axial load with compressive force (C_p) is calculated using the following relation [24, 25]:

$$C_p = \frac{F_p}{\delta_p} \tag{1}$$

where: F_p – axial force (N),
δ_p - axial displacement of segments at the point of load action (mm).

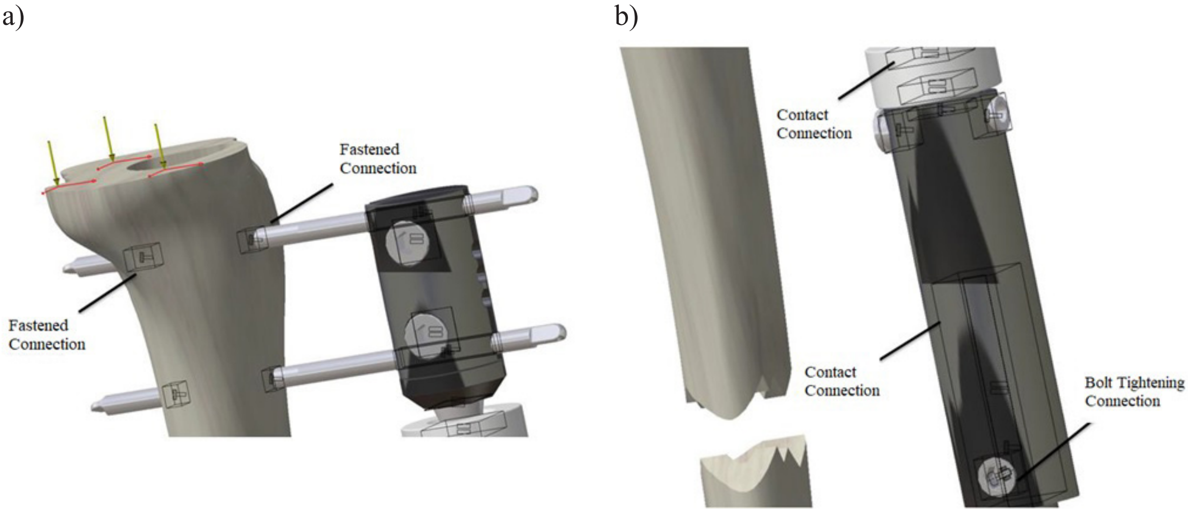

Figure 2. Defining connections on the fixator model, a) fastened connections, b) contact connections

The fracture stiffness is determined as the ratio of the load and the resulting relative displacement of the observed pair of points [26, 27]:

$$C_{pp} = \frac{F_p}{R} = \frac{F_p}{\sqrt{\left(r_{D(x)}\right)^2 + \left(r_{D(y)}\right)^2 + \left(r_{D(z)}\right)^2}} \quad (2)$$

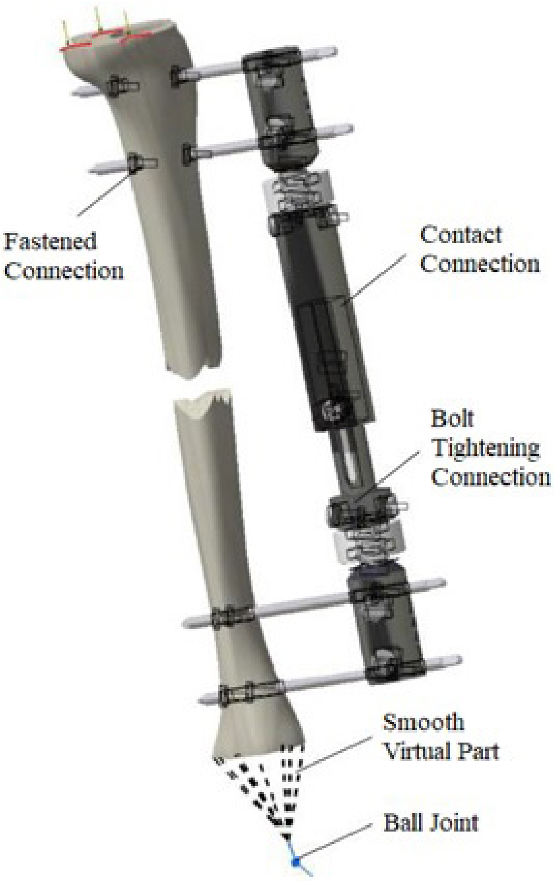

Figure 3. Fixator model with defined constraints

The relative displacements of the pairs $r_{D(x)}$, $r_{D(y)}$, $r_{D(z)}$ of observed points on the extreme planes of the proximal (upper) and distal (lower) segments of the bone model in the *x*, *y* and *z* directions are determined as [28, 29]:

$$\begin{aligned} r_{D(x)} &= D_{p(x)} - D_{d(x)} \\ r_{D(y)} &= D_{p(y)} - D_{d(y)} \\ r_{D(z)} &= D_{p(z)} - D_{d(z)} \end{aligned} \quad (3)$$

RESULTS

Figure 5 presents the vectors of displacement of points at maximum axial load where the direction, direction and intensity of the vectors of displacement of the analyzed points can be clearly seen. Also, it is possible to determine the components of the displacement vector (Table 3).

For the analysis of the stiffness of the structure loaded under pressure, the axial displacement of the central point at the place of loading of the proximal segment of the bone model in the z – axis direction was observed. Using relations (3), the relative displacements of the analyzed endpoints of the proximal and distal segments for which the relative displacement vector at the fracture site has the maximum value were determined.

The maximum displacement at the fracture site is located at the upper segment of the bone model, ie at the end of the segment and it is 3.34 mm, while the maximum displacement value at the structure is at the ends of the fixation wedges and is 2.68 mm (Figure 5).

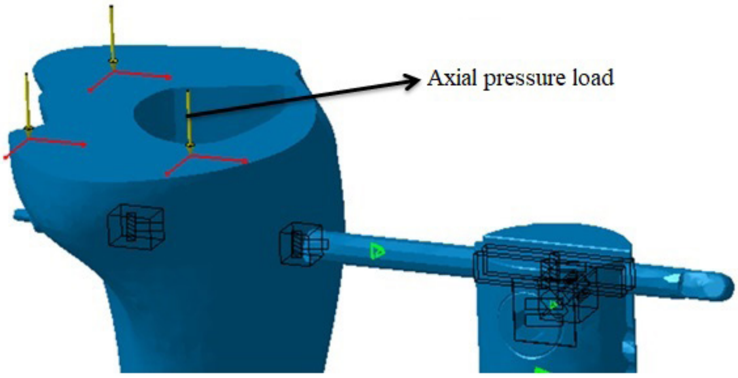

Figure 4. Defining the load on the fixator model

Stress intensities are variable as well as displacements, and they depend on the shape of the structure, ie individual parts on the structure as well as the position of the parts themselves within the structure. The most critical points on the structure are the neck of the ball and the point of contact of the coupling and the half-wedges (Figure 6).

The intensities and directions of the principal stresses were monitored at 5 critical points for the case of maximum axial pressure load (Figure 7), and the results are shown in Table 4.

DISCUSSION

FEM analysis showed that the maximum displacement at the fracture site is located at the upper segment of the bone model, ie at the very end of the segment and it is 3.34 mm, while the

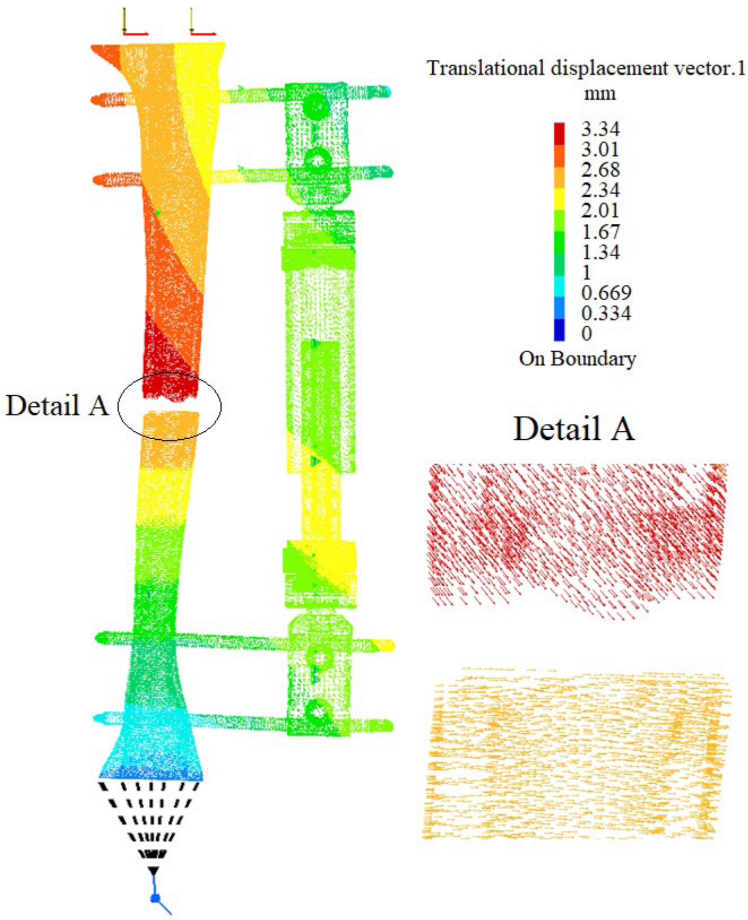

Figure 5. Point displacement vectors at maximum axial pressure load

Table 3. Displacement and stiffness values under maximum axial pressure load

Proximal segment displacement (mm)						Distal segment displacement (mm)			Fracture rigidity (N/mm)	Structural rigidity (N/mm)
Place of loading			Place of fracture			Place of fracture				
x	y	z	$D_{p(x)}$	$D_{p(y)}$	$D_{p(z)}$	$D_{d(x)}$	$D_{d(y)}$	$D_{d(z)}$	C_{pp}	C_p
0	0	2.475	2.57	2.131	0.015	-0.070	2.511	0.816	215.82	242.42

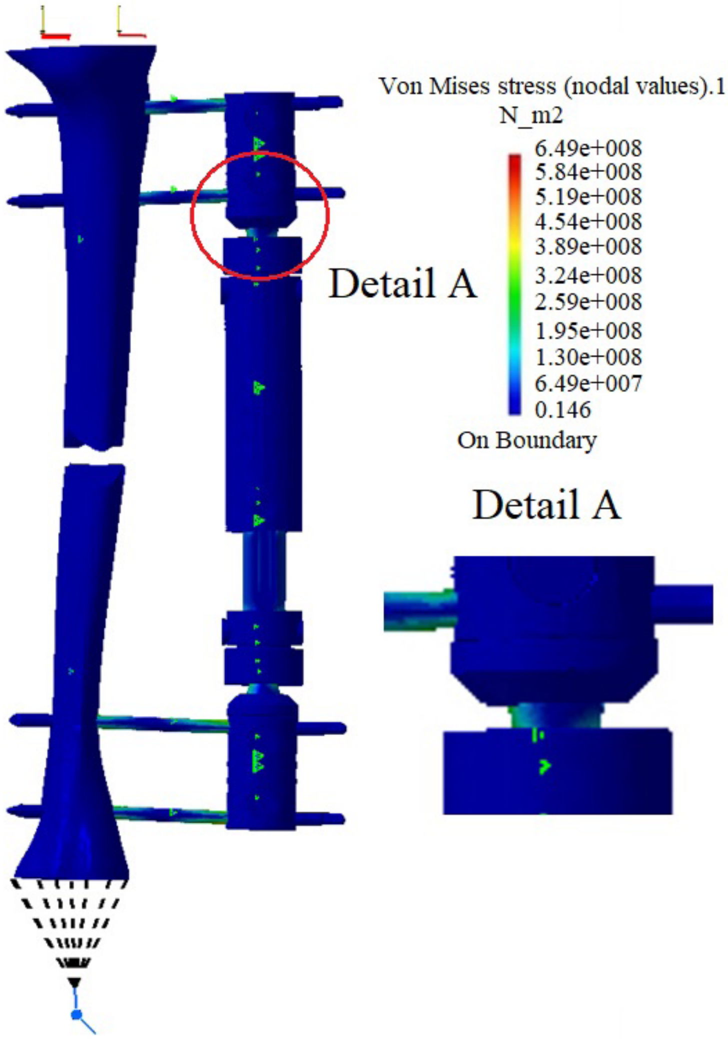

Figure 6. Distribution of von Mises stress for the case of axial pressure load

maximum displacement value at the structure is at the ends of the fixation wedges and is 2.68 mm, which is within the permissible displacements for this type of construction. Studies [9, 18] also showed similar displacement values for a similar configuration of the external fixation device loaded with the same load case.

Based on the displacement values at the fracture site and at the load site, the fracture stiffness was determined to be 215.82 N/mm, while the structural stiffness was 242.42 N/mm, which satisfies the stiffness limits for this type of structure. Studies [9, 27] also showed similar stiffness values for a similar configuration of the external fixation device loaded with the same load case.

Intensities and directions of principal stresses were monitored at 5 critical points for the case of maximum axial pressure load. The highest stress occurs at the measuring point 1, ie at the point of contact of the coupling and the half-wedge and is 202.06 MPa, which satisfies the value of the allowable stress for the material of the coupling and the half-wedge.

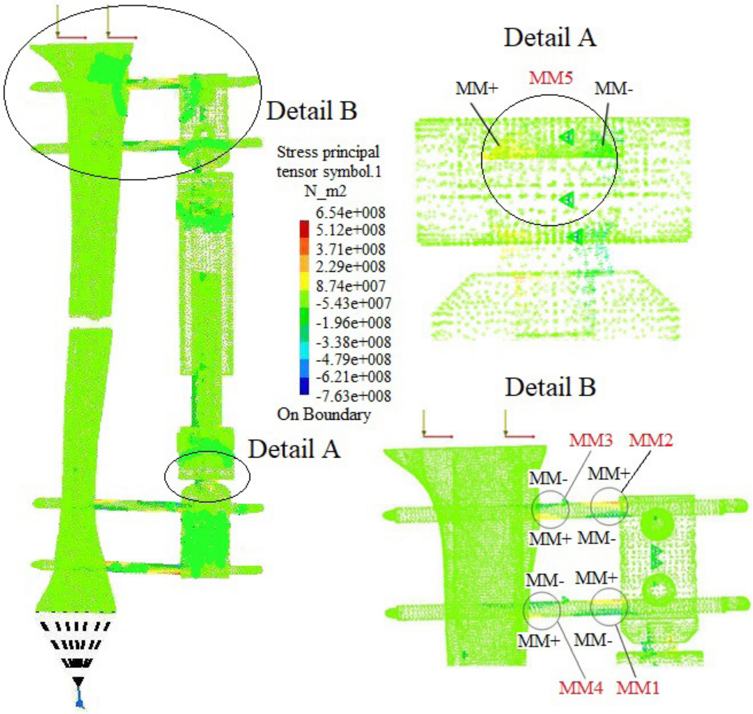

Figure 7. Principal stresses at critical points

Table 4. Stresses values under the action of maximum axial pressure load

Measuring point	Principal stresses at critical fixator locations (MPa)						Von Mises stress the critical cross section of the fixator (MPa)	
	MM+			MM-			MM+	MM-
	σ_1	σ_2	σ_3	σ_1	σ_2	σ_3	σ_{vm}	σ_{vm}
1	206.2	6.206	2.131	1.603	-7.481	-176.56	202.06	173.79
2	200.5	16.2	4.02	2.53	-0.82	-146.7	190.68	147.58
3	33.28	0.15	-1.113	1.99	-0.33	-7.7	33.78	8.76
4	35.004	-0.07	-6.01	1.25	-13.1	-22.7	38.39	20.87
5	112	2.89	-32.3	3.43	0.25	-4.48	130.31	6.89

CONCLUSIONS

The main task of the external fixator is to stabilize the fracture, as well as to improve the healing process of the bone during the healing process. According to this, it can be concluded that the mechanical characteristics of the external fixator are a very important factor in the process of fracture treatment.

In this paper, the stiffness of the Orthofix external fixator at axial pressure load was tested. In order to be able to examine the mechanical characteristics of the Orthofix external fixator, a 3D model of the fixator was first created using CATIA software. The model thus formed is the basis for FEM analysis, which will be used to study the movement of the fracture crack, the behavior of the fixator due to the action of the load, as well as the determination of the stiffness of the fixator.

Based on the results obtained from the FEM analysis, it can be concluded that the Orthofix fixator shows very good stiffness under compressive loading, but also that it is possible to improve even more by using newer materials. By using artificial materials such as composites, it will be possible in the future to obtain the same or better rigidity of the external fixation system with a significantly lower mass of fixatives, but this will require additional and extensive research.

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