Use of Stress Analysis Methods to Evaluate the Biomechanics of Oral Rehabilitation With Implants

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Because the biomechanical behavior of dental implants is different from that of natural tooth, clinical problems may occur. The mechanism of stress distribution and load transfer to the implant/bone interface is a critical issue affecting the success rate of implants. Therefore, the aim of this study was to conduct a brief literature review of the available stress analysis methods to study implant-supported prosthesis loading and to discuss their contributions in the biomechanical evaluation of oral rehabilitation with implants. Several studies have used experimental, analytical, and computational models by means of finite element models (FEM), photoelasticity, strain gauges and associations of these methods to evaluate the biomechanical behavior of dental implants. The FEM has been used to evaluate new components, configurations, materials, and shapes of implants. The greatest advantage of the photoelastic method is the ability to visualize the stresses in complex structures, such as oral structures, and to observe the stress patterns in the whole model, allowing the researcher to localize and quantify the stress magnitude. Strain gauges can be used to assess in vivo and in vitro stress in prostheses, implants, and teeth. Some authors use the strain gauge technique with photoelasticity or FEM techniques. These methodologies can be widely applied in dentistry, mainly in the research field. Therefore, they can guide further research and clinical studies by predicting some disadvantages and streamlining clinical time.

Key Words: stress analysis methods, finite element analysis, photoelasticity, strain gauge, implants
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<th>Author</th>
<th>Year</th>
<th>Study Variable</th>
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<tr>
<td>Sertgoz</td>
<td>1997</td>
<td>Three different types of occlusal material (resin, composite resin, ceramic) and 4 types of framework materials (gold, silver-palladium, cobalt-chromium, and titanium) in mandibular prosthesis with 6 implants and bone tissue</td>
<td>The optimal combination of materials was found to be cobalt-chromium for the framework and porcelain for the occlusal surface.</td>
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<tr>
<td>Arataki et al</td>
<td>1998</td>
<td>Number of implants (2 or 4), localization, structure length, presence of a distal segment, loading condition in mandibular fixed prosthesis.</td>
<td>Design to the fixture placed in a straight line; a decrease in the maximum stress value of the compact bone surrounding the fixture was recognized with a decrease in the total interfixture distance and an increase in the number of placed fixtures.</td>
</tr>
<tr>
<td>Menicucci</td>
<td>1998</td>
<td>Mandibular overdenture attachment system.</td>
<td>Resilient attachments allowed for an increase of the mastication load transiting through denture bearing surface.</td>
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<tr>
<td>Daas et al</td>
<td>2008</td>
<td>Mandibular overdenture attachment system.</td>
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<td>Tanino et al</td>
<td>2007</td>
<td>Mandibular overdenture attachment system.</td>
<td>Resilient attachments allowed for an increase of the mastication load transiting through denture bearing surface.</td>
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<tr>
<td>Pietrabissa et al</td>
<td>2000</td>
<td>Different types of framework adjustment</td>
<td>Prosthesis misfit influenced the pattern and magnitude of stress distribution in the prosthesis, implant components, and surrounding bone, and the presence of the cantilever or greater occlusal force amplified the effect of misfit.</td>
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<tr>
<td>Kunavisarut et al</td>
<td>2002</td>
<td>Different types of framework adjustment</td>
<td>Prosthesis misfit influenced the pattern and magnitude of stress distribution in the prosthesis, implant components, and surrounding bone, and the presence of the cantilever or greater occlusal force amplified the effect of misfit.</td>
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<tr>
<td>Natali et al</td>
<td>2006</td>
<td>Different types of framework adjustment</td>
<td>Prosthesis misfit influenced the pattern and magnitude of stress distribution in the prosthesis, implant components, and surrounding bone, and the presence of the cantilever or greater occlusal force amplified the effect of misfit.</td>
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<tr>
<td>Akpinar et al</td>
<td>2000</td>
<td>Occusal contact between implant and natural teeth</td>
<td>High compressive stresses may contribute to intrusion of the tooth</td>
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<tr>
<td>Nagassao et al</td>
<td>2002</td>
<td>Maximum stress around implants in patients with partial mandible resection due to cancer</td>
<td>Location and intensity of the stresses occurring around fixtures differs significantly between various types of mandibular reconstruction</td>
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<td>Akca et al</td>
<td>2002</td>
<td>Insertion of a shorter implant in place of a cantilever extension on stress distribution compared with cantilevered fixed prosthesis in posterior mandibular edentulism.</td>
<td>Significant lower stress values were recorded at the shorter implant placement configurations than the cantilevered prosthesis. Posterior cantilever extension performed higher stress values than the anterior counterpart.</td>
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<tr>
<td>Lang et al</td>
<td>2003</td>
<td>Preload of implant system</td>
<td>A preload of 75% of the yield strength of the abutment screw was not established using the recommended tightening torques.</td>
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<td>Tada</td>
<td>2003</td>
<td>Implant design and bone type</td>
<td>Cancellous bone of higher rather than lower density might ensure a better biomechanical environment for implants</td>
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<td>Geng et al</td>
<td>2004</td>
<td>Conical implant screw design</td>
<td>Minimal support constraints allow clearer differentiation of the stress picture between the different stepped screw types at the trabecular bone-implant interface</td>
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<td>Sevimay et al</td>
<td>2005</td>
<td>Four types of mandibular bone quality</td>
<td>Simulating different bone qualities for an implant-supported crown affected stress distribution and stress values</td>
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success rate of implants. Overload can lead to mechanical complications and bone loss. In addition, implant-supported prostheses present a better biomechanical behavior when no excessive occlusal force is transmitted.

Therefore, it is essential to understand and improve the load distribution from the prosthesis to the implants and bone. During the past three decades, researchers in this area have emphasized the importance of the biomechanical aspect of implant treatments, and they have sought to define the limit of force transmission to the implants and to develop methods to evaluate the biomechanics of dental implants.

Direct clinical evaluation (immediate or longitudinal) would be the surest method to analyze the biomechanical response of implant treatment. However, the complexity of the structures involved makes direct clinical evaluation of the biomechanical behavior of intraosseous structures nearly impossible, considering the difficulty of the methodology, the potential ethical issues, and the long period of time that would be required for this type of study.

To overcome these limitations, several studies have used computational, analytical, and experimental models by means of finite element analysis, photoelasticity, and strain gauges to evaluate the biomechanics of dental implants. In order to reduce the limitations and determine the advantages of each of these methods, several studies have used a combination of these methods as they have been shown to be complementary. The aim of the present study was to conduct a literature review of the stress analysis methods used to investigate the biomechanical behavior of implant-supported...
finite element method

The finite element method (FEM) was developed in the early 1960s by the aerospace industry, and its use has spread. In 1976, Weinstein et al. were the first researchers to use the FEM in the implantology field. Since then, several studies have used this method to evaluate new components, configurations, materials, and shapes of implants.

The FEM uses virtual models to simulate and test the progressive resistance and stress distribution of complex structures. According to FEM studies, this method enables the investigation of mechanical problems, dividing the element-problem into many smaller and simpler elements to create a mesh of elements and to solve the problem by using mathematical functions. Thus, it is possible to simulate and evaluate the biomechanical behavior of bone, implants, and prosthetic components interfaces, which would be impossible to analyze experimentally in vitro or in vivo. The FEM enables researchers to apply different loadings and to obtain the displacement and the stress levels this load causes on the tooth, prosthesis, implant, and bone.

The mechanical modeling of the structures can be performed in 2 or 3 dimensions. The 3-dimensional analysis allows for the development of models that are more true to real life and have complex geometry, thereby creating more consistent results.

However, the FEM has some disadvantages and criticisms. An important issue is the creation of very complex models. Some simplifications and assumptions must be made to make the solution possible, which affects the final result. Some simplifications and assumptions usually adopted in studies of dental implants are simplification of the geometry of bone or implant system assuming that the bone is homogeneous and isotropic, boundary conditions, inconsistent type of bone-implant interface, etc.

The FEM has been widely used in dental implantology as described in Table 1.

photoelasticity

The photoelastic analysis was introduced in dentistry by Noona in 1949. Since then, this method has been widely used in restorative dentistry. In the implantology field, photoelasticity was first used by Haraldson in 1980 to assess the quality of fringes at different levels of implant insertion.

The photoelastic analysis technique is based on the optical property of certain colorless plastic materials that, when subjected to stress/deformation, present alterations on the refraction indices (or optical anisotropy) promoting color change.

The greatest advantage of the photoelastic method is the ability to visualize the stresses in complex structures, such as oral structures, and to observe the stress patterns in the whole model, allowing the researcher to localize and quantify the stress magnitude.

Experimental tests using the photoelasticity technique have been applied in several studies involving an implant-supported prosthesis to evaluate stress distribution. This method allows for the qualitative analysis of stress.
through the observation of optical effects in the photoelastic models.\textsuperscript{52,54} Stresses inside the models can be measured and photographed, whereas in other analytical methods, graphs and diagrams of stress distribution must be constructed from numeric data.\textsuperscript{1,2,8,15,18,52–55} The photographic records are qualitatively analyzed to investigate the propagation and intensity of stress. Most of the stress evaluations are performed visually. In 1995, Mahler and Peyton,\textsuperscript{54} described the sequence of fringes based on the

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<td>Hellénden and Derand\textsuperscript{56}</td>
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<td>Kenney and Richards\textsuperscript{57}</td>
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<td>Sadowswsky and Caputo\textsuperscript{58}</td>
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<td>Sadowswsky and Caputo\textsuperscript{59}</td>
<td>2004</td>
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<td>Celik et al\textsuperscript{13}</td>
<td>2007</td>
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<td>Ochiai et al\textsuperscript{60}</td>
<td>2003</td>
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<td>Ueda et al\textsuperscript{9}</td>
<td>2004</td>
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<td>Markarian et al.\textsuperscript{61}</td>
<td>2007</td>
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<td>Barbosa et al.\textsuperscript{55}</td>
<td>2008</td>
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<td>Golato et al\textsuperscript{2}</td>
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<td>Bernardes et al\textsuperscript{1}</td>
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<td>da Silva et al\textsuperscript{62}</td>
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<td>Pellizzer et al\textsuperscript{63}</td>
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<tr>
<td>Glantz et al</td>
<td>1993</td>
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<td>Wang et al</td>
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<td>Duyck et al</td>
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<td>Watanabe et al</td>
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<td>Bassit et al</td>
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<td>Heckmann et al</td>
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<td>Naconecy et al</td>
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<td>Cehreli et al</td>
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<td>Karl et al</td>
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<td>Hegde et al</td>
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<td>Karl et al</td>
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<td>Author</td>
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<tr>
<td>Nishioka et al</td>
<td>2009</td>
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<tr>
<td>Nishioka et al</td>
<td>2011</td>
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<td>Rungsiyakull et al</td>
<td>2011</td>
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<td>Yang et al.</td>
<td>2011</td>
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<tr>
<td>Nissan et al</td>
<td>2011</td>
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**Figure 2.** The maximum equivalent Von Mises stress on the implant.
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<td>Clelland et al</td>
<td>1995</td>
<td>Strain gauge and photoelasticity</td>
<td>Different misfit in overdenture</td>
<td>Strains were transferred to the bone when misfitting prostheses were secured.</td>
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<tr>
<td>Brosh et al</td>
<td>1998</td>
<td>Strain gauge and photoelasticity</td>
<td>Straight and tilted implants</td>
<td>Data obtained from strain gauges bonded to implants embedded in a medium can represent a precise simulation of the clinical condition when analyzing stress distribution along the implant/bone interface. Photoelasticity provides different information and therefore should be regarded as a complementary method.</td>
</tr>
<tr>
<td>Kim et al</td>
<td>1999</td>
<td>Strain gauge and photoelasticity</td>
<td>Prosthesis retained by temporary luting agent, permanent luting agent, and screwed</td>
<td>In 2-implant supported distal cantilevered prostheses, the screw-type and the permanent-cement retained prostheses developed more stress around the apex of both implants. The permanent-cement-retained prostheses acted almost the same as the screw type.</td>
</tr>
<tr>
<td>Akça et al</td>
<td>2002</td>
<td>Strain gauge and FEM</td>
<td>Dental implants submitted to vertical and oblique forces</td>
<td>There is compatibility between nonlinear finite element stress analysis and in vitro strain gauge analysis on the measurement of strains under vertical loading. However, there are differences between the methods in quantification of strains on the collar of implants under lateral loading.</td>
</tr>
<tr>
<td>Iplikçioglu et al</td>
<td>2003</td>
<td>Strain gauge and FEM</td>
<td>Effectiveness of reflective photoelasticity as a technique for in vivo monitoring</td>
<td>Reflective photoelasticity is a valid, reliable, and accurate technique that may be used for in vivo studies on the biomechanical behavior of prosthetic devices.</td>
</tr>
<tr>
<td>Fernandes et al</td>
<td>2003</td>
<td>Strain gauge and photoelasticity</td>
<td>Different types of implant/abutment systems</td>
<td>Butt-joint and internal-cone oral implants have similar force distribution characteristics. The implant-abutment mating design is not a decisive factor affecting stress and strain magnitudes in a bone simulant.</td>
</tr>
<tr>
<td>Çehreli et al</td>
<td>2004</td>
<td>Strain gauge and photoelasticity</td>
<td>Passivity in screwed and cemented fixed prostheses</td>
<td>The level of precision of fit that can be obtained in superstructure fabrication would appear sufficient to produce restorations that do not cause bone damage.</td>
</tr>
<tr>
<td>Karl et al</td>
<td>2006</td>
<td>Strain gauge and FEM</td>
<td>Tooth/implant-supported fixed prostheses with rigid and nonrigid connectors</td>
<td>If tooth and implant abutments are to be used together as fixed prostheses supports, nonrigid connectors should be placed on the implant abutment-supported site.</td>
</tr>
<tr>
<td>Ozcelik et al and Ersoy</td>
<td>2007</td>
<td>Photoelasticity and FEM</td>
<td>Different types of conical implants</td>
<td>To reduce stresses in the peri-implant region, implant diameter may be more effective than type of implant.</td>
</tr>
</tbody>
</table>
values of fringe order (N): 0 (black), 1 (transition of red/blue), 2 (transition of red/green), 3 (transition of pink/green) as reference for comparisons between samples in vitro. The higher the N (fringe order) and fringes number are, the greater the stress intensity. And the closer the fingers are, the higher the stress concentration (Figure 1)∗.

According to Goiato et al, 3 techniques of photoelasticity are available: 2-dimensional, 3-dimensional, and quasi-3-dimensional (the model is 3-dimensional but the fringes are observed and analyzed in 2 dimensions). In addition, the reflection photoelasticity technique has been described. In 2003, Fernandes et al showed the effectiveness of reflective photoelasticity as a quantitative technique, and similar stress values were noted when compared with the strain gauge technique. Thus, the authors considered reflective photoelasticity to be a valid, applicable, and necessary method to evaluate the biomechanical behavior of in vivo structures. However, this technique has had limited study, so further studies are warranted.

Photoelasticity also presents some limitations. Because it is an indirect technique, it requires similar patterns of reproduction to be compared with clinical situations. Another factor to consider is the limit of applied external force, which may not exceed the limit of resistance of the photoelastic material; this could alter the outcome or promote material rupture. Although the resin used to fabricate the experimental models has an elasticity modulus similar to bone tissue, no differentiation between cortical and trabecular bones is possible, which alters the magnitude of stress induced by the load. However, not only the stress location but also the stress behavior are similar to those observed clinically.

Currently, photoelasticity has been used to evaluate stress in implant-supported prosthesis and bone tissue in several studies that simulate the mechanical-clinical situations presented in this type of rehabilitation, as shown in Table 2.

**Strain Gauges**

Strain gauges are small electric resistors that under slight deformation alter the resistance created in their current. They measure the deformation of an object where they are applied. The captured electrical signal is sent to a data acquisition board, turned into a digital signal, and read by the computer. The gauges are able to precisely record the deformation of any object subjected to stress. Strain gauges can be used to assess stress in prostheses, implants, and teeth both in vivo and in vitro. Methods based on strain gauges have been used to calculate rather than measure tissue stress and strain. The use of a strain gauge to evaluate the stresses induced in the implants presents clinical reliability. In numeric analysis, several assumption are necessary to represent the physical problem into a mathematical model, and this accuracy should be checked. Some authors use the strain gauge technique along with either the photoelasticity technique or the FEM.

However, there is no conclusive information about the ideal model to perform this type of study.

### Table 4

*FEM indicates finite element model.*

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<tr>
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<tr>
<td>Eser et al.</td>
<td>2009</td>
<td>Strain gauge and FEM</td>
<td>Evaluate the level of agreement between nonlinear finite element stress analysis and ex vivo strain gauge analysis on immediately loaded implants</td>
<td>Considering the complex biomechanical behavior of human hard and soft tissues, ex vivo strain gauge analysis and nonlinear finite element stress analysis did not suggest inconsistency in the detection of the quality of strains. Further, the methods provided comparable values for the quantification of strains on implants supporting maxillary overdentures.</td>
</tr>
</tbody>
</table>

*References 2, 13, 15, 18, 51, 54, 55, 57, 60, 61.*
Some claimed to place the strain gauges directly on prosthetic pieces, while others indicated that they placed the gauges on similar bone material. Strain gauges have been used extensively on bone in vivo or ex vivo and even in coagulum around immediate implants, but the measurements are limited to the area where the gauge is bonded or embedded.

The use of strain gauge to evaluate stresses induced on the implants is reliable, as observed in the literature (Table 3).

**DISCUSSION**

Laboratory and clinical research has shown that the clinical success and the longevity of dental implants can be controlled by biomechanical factors in most cases. Also, the load should be transmitted to the bone in a manner similar to the physiological way. Furthermore, changes in the magnitude and distribution of load can affect the quality and quantity of stress in a prosthesis/implant/bone system.

The biomechanical mechanisms related to implant failure remains unknown. Bone resorption, fracture, and loss of implant linked to biomechanical factors are inconclusive. Understanding these factors is necessary for the development and mastery of new techniques and protocols to treat edentulous patients.

The stress analysis as photoelastic resin model and 2- and 3-dimensional FEM are limited to a single structure. Some authors consider those methods unreliable, as they do not allow the quantification of stress. Methodologies that enable the analysis of stress generated directly on the implant-retained systems via elastic deformation, such as strain gauges, have been broadcast. However, when complex geometry is involved in the analysis, it is difficult to determine the analytical solution; therefore, the FEM, by using numeric procedures, helps to solve this problem in order to understand the mechanical behavior and calculate the stress.

According to these studies, by understanding the basic theory, method, application, and limitations of the FEM, clinicians can interpret the results of this methodology and extrapolate the results to clinical situations. In the FEM, von Mises stress distribution indicates that stress is great around the top of the implant, bone, and prosthetic structure with different intensities in different loading cases, as illustrated in Figure 2.

Similar to the FEM, photoelasticity can be evaluated in 2 or 3 dimensions. Additionally, both techniques require similar patterns of reproduction in order to be compared with clinical situations.

On the other hand, strain gauge analysis can be used to assess stress in prostheses, implants, and teeth both in vivo and in vitro. The Reflective photoelasticity can also be used in vivo.

Based on several studies no one method can be classified as better than the others. Thus, there is consensus among the researchers that all methods are complementary, and this association has been used as described in Table 4.

**CONCLUSION**

Numeric methods of stress analysis estimate stress level with high accuracy in terms of intensity and location. The FEM has been used to evaluate new components, configurations, materials, and shapes of implants. The greatest advantage of the photelastic method is the ability to visualize the stresses in complex structures, such as oral structures, and to observe the stress patterns in the whole model, allowing the clinician to localize and quantify the stress magnitude. Strain gauges can be used to assess stress in prostheses, implants, and teeth both in vivo and in vitro. Some authors use the strain gauge technique accompanied by either the photoelasticity technique or the FEM.

These methodologies can be widely applied in dentistry, mainly in the research field. Therefore, they can guide further research and clinical studies by predicting some disadvantages and streamlining clinical time.

**ABBREVIATION**

FEM: finite element model

**REFERENCES**


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