Journal of Oral Rehabilitation 2003 **30**; 936–943

Stress analysis of an upper central incisor restored with different posts

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SUMMARY The effect of different anatomic shapes and materials of posts in the stress distribution on an endodontically treated incisor was evaluated in this work. This study compared three post shapes (tapered, cylindrical and two-stage cylindrical) made of three different materials (stainless steel, titanium and carbon fibre on Bisphenol A-Glycidyl Methacrylate (Bis-GMA) matrix). Two-dimensional stress analysis was performed using the Finite Element Method. A static load of 100N was applied at 45° inclination with respect to the incisor's edge. The stress concentrations did not significantly affect the region adjacent to the alveolar bone crest at the palatine portion of the tooth, regardless of the post shape or material. However, stress concentrations on the post/dentin interface on the palatine side of the tooth root presented significant variations for different post shapes and materials. Post shapes had relatively small impact on the stress concentrations while post materials introduced higher variations on them. Stainless steel posts presented the highest level of stress concentration, followed by titanium and carbon/Bis-GMA posts.

KEYWORDS: teeth, restoration, posts, bioengineering, stress analysis, finite element method

Introduction

Restoration of endodontically treated teeth is still a controversial subject on present days. It is known that those teeth are generally weaker because of dental structure loss, cavities, filling preparation and root canal instrumentation. It is also important to point out that dentin moisture decrease would lower their strength properties making them more susceptible to fractures (Helfer, Melnick & Schilder, 1972). Therefore, special care is indicated when selecting the most efficient way to restore them.

Dentistry has searched for an ideal approach to reconstruct endodontically treated teeth in a way that it would offer protection to the remaining dental structure. Cast metallic cores have been the most popular technique for reconstruction of those teeth. Several authors claim that these cast metallic cores best reach their goals because they are tougher, more versatile and fit better to the root canal (Hirschfeld & Stern, 1972; Perel & Muroff, 1972; Kantor & Pines, 1977; Gelfand, Goldman & Sunderman, 1984; Plasmans, Welle & Vrijhoef, 1988; Bex *et al.*, 1992). However, this reconstruction technique presents some disadvantages such as more clinical sessions, use of laboratory procedures, higher costs and more healthy tissue removal to allow cast moulding, compared with the core and post technique.

The alternative technique uses composite resin cores associated or not to posts. Although composite resin cores presents some disadvantages such as thermal mismatch with the remaining dental structure and undesirable contraction during the process of resin cure, the associated technique results in more preservation of healthy tissue, time savings for patients and professionals, lower costs, higher ultimate strength and no necessity of laboratory procedures. Ti-Core* was selected as the composite resin for this analysis.

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*Essential Dental Systems, Inc., S. Hackensack, NJ, USA.

Materials and method

The Finite Element Method (FEM) was selected to perform the stress analysis of the tooth. This method is particularly suitable to biological structure analysis as it allows great flexibility in dealing with geometric complex domains composed by multiple materials. In this work the university version of the code ANSYS[†] was used as platform. Finite element models, however, assume that materials are idealized as homogeneous and generally isotropic which may introduce errors on the results. Furthermore, interfaces are assumed perfectly bonded. The use of the correct load level and direction as well as the selection of suitable boundary conditions are also important definitions for a realistic analysis.

Two-dimensional (2-D) elastic analysis was used for simplification purposes. The upper central incisor domain was defined by its cross-section, which geometry was obtained from Wheeler (1969). Plane strain was considered in the analysis, meaning an infinitely long tooth normal to its cross-section. Although controversial, this hypothesis can be considered reasonable for the tooth in question because its cross-section is relatively constant along its normal axis. Such hypothesis allowed 2-D analysis and was proved satisfactory as shown by Tresher and Saito (1973), Davy, Diley and Krejci (1981), Reinhardt *et al.* (1983), and especially by Ko *et al.* (1992), where plane stress, plane strain and axisymmetric models were discussed. Furthermore the use of 2-D analysis in this study is adequate as it is focused on qualitative comparison of stress patterns among different post materials and design, which does not justify the high computational costs associated to modelling and analysing three-dimensional (3-D) domains. Results, however, should not be analysed isolated.

Stress patterns as a factor of post shape and material were already recorded in the literature using 2-D (Davy, Diley & Krejci, 1981; Reinhardt *et al.*, 1983; Cailleteau, Rieger & Akin, 1992; Ko *et al.*, 1992) and 3-D (Ho *et al.*, 1994; Holmes, Diaz-Arnold & Leary, 1996; Yaman, Alaçam & Yaman, 1998) finite element analysis. However, this study was motivated by the use of selected posts of different shapes and materials so that a comparison could be made. The upper central incisor was selected because it is a single-root tooth with relatively simple anatomy and highly susceptible to fracture.

This analysis considered anatomy based geometric structures for the enamel, dentin, pulp, porcelain crown, cortical bone, sponge bone, remaining root canal filling using gutta-percha and posts. Figure 1 shows the complete geometry of the four used models, as defined below:

(1) Incisor 1: healthy tooth composed by enamel, dentin, pulp, cortical bone and sponge bone as shown in Fig. 1(a);

(2) Incisor 2: restored tooth composed by porcelain crown, dentin, tapered post, cortical bone, sponge bone, root canal gutta-percha filling as shown in Fig. 1(b);

(3) Incisor 3: restored tooth composed by porcelain crown, dentin, cylindrical post, cortical bone, sponge bone, root canal gutta-percha filling as shown in Fig. 1(c);

(4) Incisor 4: restored tooth composed by porcelain crown, dentin, two-stage cylindrical post, cortical bone, sponge bone, root canal gutta-percha filling as shown in Fig. 1(d).

Three anatomic geometric models for root posts were considered as also shown in Fig. 1:

(1) tapered post, based on the Unimetric post[‡] (12 mm length, 1 mm apical diameter and 2 mm coronal diameter) with smooth surface (Fig. 1b);

(2) cylindrical post (12 mm length and 1·4 mm diameter) (Fig. 1c);

(3) two-stage cylindrical post (12 mm length, 1·8 mm larger diameter and 1·2 mm smaller diameter) (Fig. 1d).

Domains were meshed using plane quadrilateral elements with four nodes. Meshes were pre-analysed and refined on the stress concentration regions. Figure 1(e–h) show their final aspect for the four domains, respectively, for incisors 1, 2, 3 and 4. The number of degrees of freedom for the considered meshes was balanced (Table 1) keeping all meshes' numerical error in the same level for comparison of results. Meshes used were more refined than others found in the literature, for both 2-D (Davy *et al.*, 1981; Reinhardt *et al.*, 1983; Cailleteau *et al.*, 1992; Ko *et al.*, 1992) and 3-D (Ho *et al.*, 1994; Holmes *et al.*, 1996; Yaman *et al.*, 1998) analysis.

Also for simplification purposes, all materials were considered homogeneous, isotropic, and linearly elastic, except the carbon-fibre/Bis-GMA posts, considered orthotropic with different material properties on fibre

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[†] ANSYS, Canonsburg, PA, USA.

[‡] Les Fils D. Auguste Maillefer S.A., Baillaigues, Switzerland.

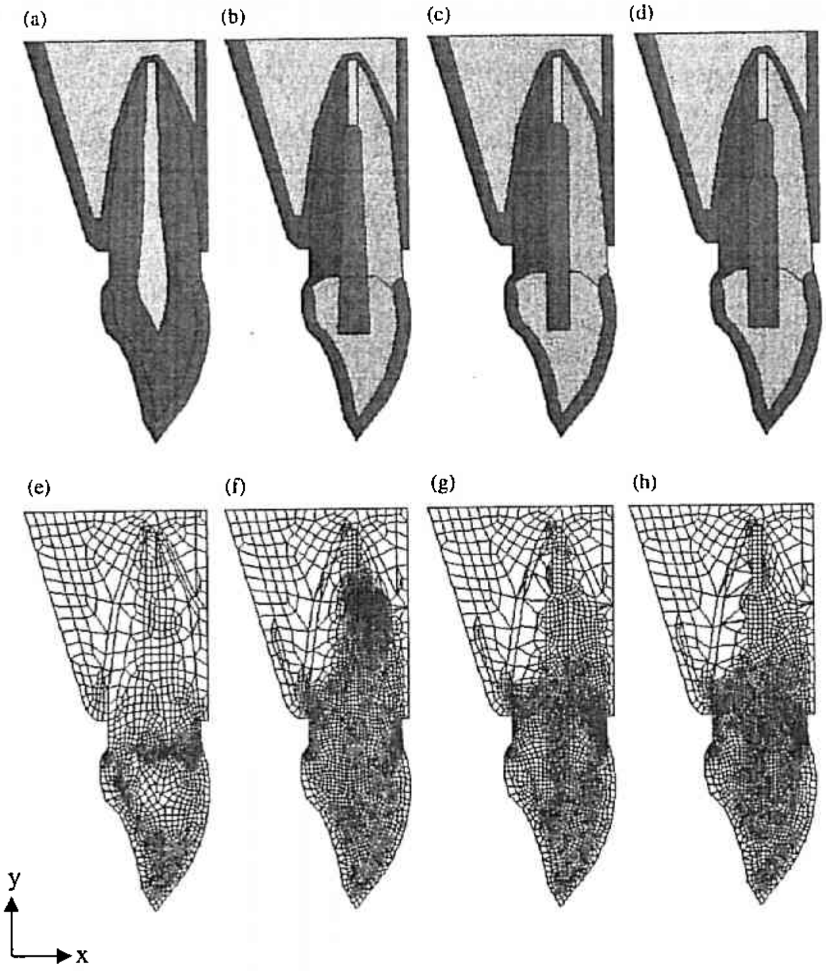


Fig. 1. Domain geometry (a–d) and finite element meshes (e–h) for the studied incisors (respectively incisors 1, 2, 3 and 4).

Table 1. Information on used meshes

Model	Post anatomic shape	Number of elements	Number of nodes	Number of degrees of freedom
Incisor 1	Healthy tooth	1509	4634	9190
Incisor 2	Tapered	2870	8695	17 312
Incisor 3	Cylindrical	2506	7595	15 112
Incisor 4	Two-stage cylindrical	2612	7921	15 764

in parallel and perpendicular directions. The fibres in this case were aligned to the post longitudinal axis. Homogeneity and isotropy have been largely adopted for dental tissues in the literature as available data of their mechanical properties yet do not incorporate information on non-homogeneity and anisotropy inherent to those materials. References for those properties are generally related to work developed some time ago. However, there is an ongoing effort to fulfil this lack of information in more recent studies (Spears *et al.*, 1993; Spears, 1997). Table 2 shows the material properties used on this study and the references from where they were obtained (Rubin *et al.*, 1983; Clelland *et al.*, 1991; Ko *et al.*, 1992; Cohen *et al.*, 1997; Yaman *et al.*, 1998).

As in Ho *et al.* (1994) and Holmes *et al.* (1996), a 100-N load was applied on the upper central incisor palatine region close to its incisal edge as shown in Fig. 2. The load was 45° tilted with respect to the tooth's longitudinal axis in order to simulate the centric occlusal contact with the opposite tooth. For all models total restraining of the degrees of freedom was imposed

Table 2. Material properties used in the finite element models

Material	Young's modulus (GPa)	Poisson's ratio	Reference
Enamel	41	0·30	Ko *et al.* (1992)
Dentin	18·6	0·31	Ko *et al.* (1992)
Pulp	0·002	0·45	Rubin *et al.* (1983)
Cortical bone	13·7	0·30	Ko *et al.* (1992)
Sponge bone	1·37	0·30	Ko *et al.* (1992)
Gutta-percha	0·00069	0·45	Ko *et al.* (1992)
Porcelain	69	0·28	Yaman *et al.* (1998)
Compose resin/core (Ti-Core)	22·2	0·30	Cohen *et al.* (1997)
Stainless steel	200	0·33	Ko *et al.* (1992)
Titanium	103·4	0·33	Clelland *et al.* (1991)
Carbon fibre on Bis-GMA matrix			
Parallel to fibres	129	0·33	Bisco Dental Products[‡]
Perpendicular to fibres	9·62	0·33	Bisco Dental Products[‡]

[‡] Bisco Dental Products, Itasca, IL, USA.

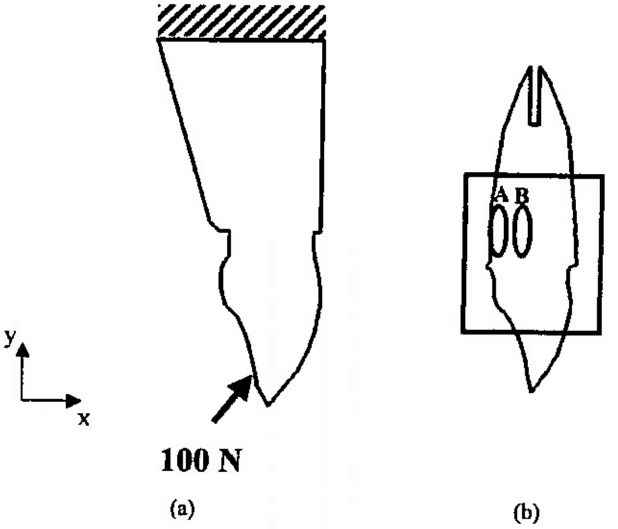


Fig. 2. Model loading and boundary conditions (a), and simplified geometry highlighting the stress analysis region of interest also including tensile stress concentration areas A and B (b).

on the nodes at the upper horizontal line. This condition simulates perfect clamping on the upper region of the models, corresponding to the terminal bone portion (Fig. 2).

Results

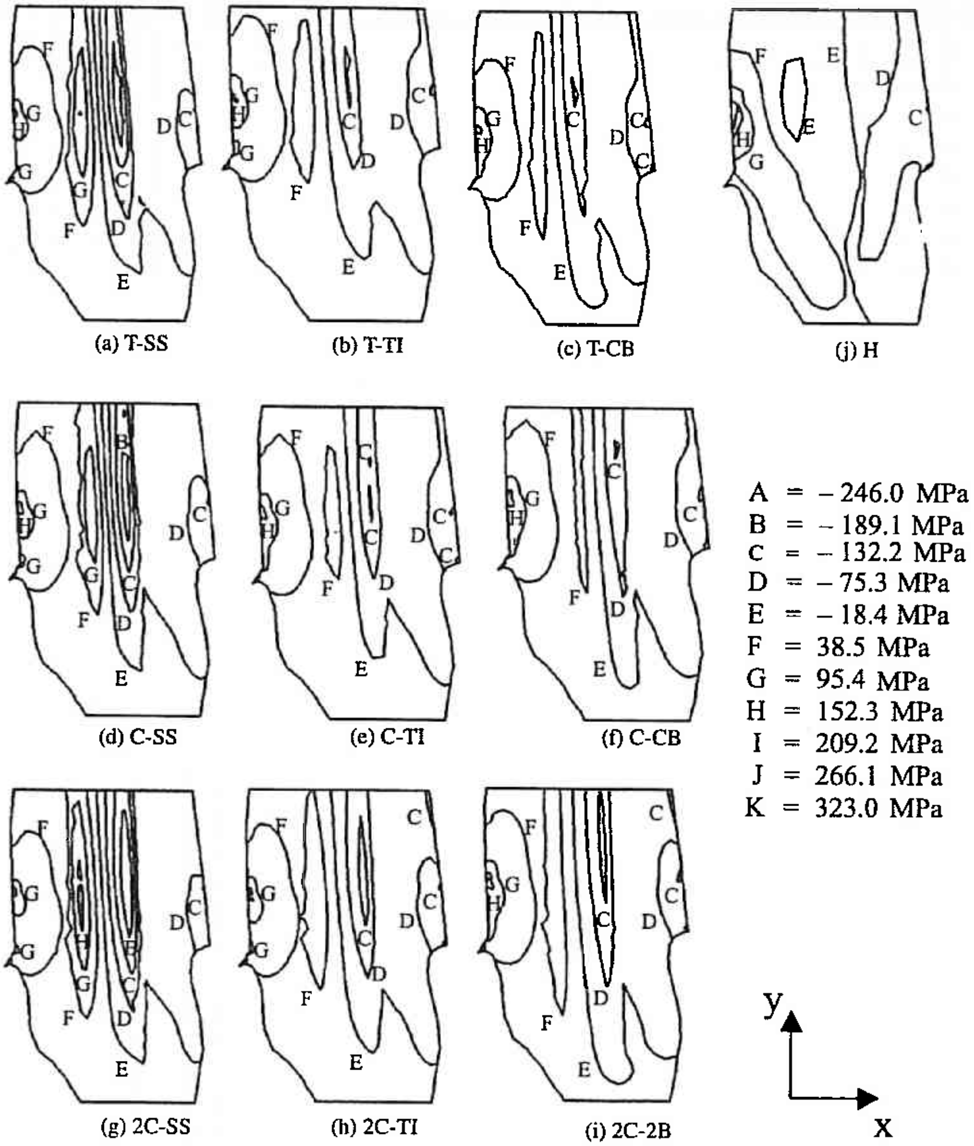
Ten different analyses were conducted: one of them on the healthy tooth (Incisor 1; Fig. 1a) and the other nine corresponding the use of three different post materials (stainless steel, titanium and carbon/Bis-GMA) into the three different post geometric models (tapered – Incisor 2, Fig. 1b; cylindrical – Incisor 3, Fig. 1c; and two-stage cylindrical – Incisor 4, Fig. 1d).

Simplified geometry of the defined models is shown on Fig. 2 for best presentation of the stress analysis results. This simplified geometry excludes the bone support and only considers the tooth's internal structure in order to focus on the region of interest.

Figure 3 shows the distribution of the stresses on y direction, σ_y, for the different models in a matrix presentation form. The matrix lines present the three different post geometric models (respectively tapered, cylindrical and two-stage cylindrical) and the matrix columns present the three different materials used on those models (respectively stainless steel, titanium and carbon/Bis-GMA). The healthy tooth results are presented on the upper right corner (Fig. 3j). Therefore, Fig. 3(a) represents the results for the tapered post of stainless steel, Fig. 3(b) for the tapered post of titanium, Fig. 3(c) for the tapered post of carbon/Bis-GMA, Fig. 3(d) for the cylindrical post of stainless steel, Fig. 3(e) for the cylindrical post of titanium, Fig. 3(f) for the cylindrical post of carbon/Bis-GMA, Fig. 3(g) for the two-stage cylindrical post of stainless steel, Fig. 3(h) for the two-stage cylindrical post of titanium and Fig. 3(i) for the two-stage cylindrical post of carbon/Bis-GMA. Tables 3 and 4 list σ_y values observed on the main stress concentration regions for the analysed models.

Discussion

Stress on global coordinate system y direction (Fig. 1) was considered as representative on this study because



Post shape:
T – Tapered
C – Cylindrical
2C – Two-stage cylindrical

Post material:
SS – Stainless steel
TI – Titanium
CB – Carbon fiber on BIS-GMA

H – Healthy tooth

Fig. 3. Detail of stress distribution on *y* direction (σ_y) for the studied cases.

it is associated to normal loading because of the bending of the dental structure. Indeed this is a cantilever-beam-like problem where the stress on *y* direction is the major contributor to the equivalent Von Mises stress. Furthermore, the analysis was focused only on regions submitted to tensile stress as the failure mechanism observed for this kind of problem is normally dentin brittle fracture in tension.

In all models, including the healthy tooth model, a stress concentration region was identified on the dentin at the cervical region on the palatine side of the tooth, as showed in Fig. 3. The maximum tensile stresses are located on this region. It can also be observed that changes on both geometry or post material have no significant impact on this stress concentration, also present on the healthy tooth, as shown on Table 3.

Table 3. Maximum dentin tensile stresses on *y* direction (σ_y) at the cervical region of the tooth palatal side (region A on Fig. 2b)

Model	Post anatomic shape	Without post	Stainless steel (MPa)	Titanium (MPa)	Carbon/Bis-GMA (MPa)	Maximum stress reduction (%)
Incisor 1	Healthy tooth	293 MPa	–	–	–	–
Incisor 2	Tapered	–	298·7	308·8	322·5	7
Incisor 3	Cylindrical	–	296·0	304·5	317·6	7
Incisor 4	Two-stage cylindrical	–	283·7	299·6	318·2	11
Maximum stress reduction (%)		–	5	3	2	

Table 4. Maximum dentin tensile stresses on *y* direction (σ_y) at the post/dentin interface of the root coronal third (region B on Fig. 2b)

Model	Post anatomic shape	Without post	Stainless steel (MPa)	Titanium (MPa)	Carbon/Bis-GMA (MPa)	Maximum stress reduction (%)
Incisor 1	Healthy tooth	−42·8 MPa	–	–	–	–
Incisor 2	Tapered	–	132·1	75·9	59·5	55
Incisor 3	Cylindrical	–	112·1	61·9	45·7	59
Incisor 4	Two-stage cylindrical	–	125·3	76·6	62·5	50
Maximum stress reduction (%)		–	15	19	27	

Ho *et al.* (1994) also found the same kind of stress concentration on this region and observed that the maximum stress is higher for posts with lower stiffness, although this effect is minor being around 10%. Indeed higher modulus posts increase tooth stiffness thus reducing the stress concentration level on its cervical portion (Cailleteau *et al.*, 1992). According to Trabert, Caput and Abou-Rass (1978) the use of smaller diameter posts is recommended as they preserve a larger portion of dentin thus reducing the stress concentration on the referred region.

Another stress concentration region was observed on Fig. 3, corresponding to the post/dentin interface on the palatine side of the coronal third of the root. A more detailed analysis of this region showed that the higher tensile stresses are located inside the post. However, the interest of this study is focused on the dentin tensile behaviour in the presence of posts with different shapes and materials. Thus, on Table 4 it is presented the maximum tensile stresses on this interface region, so that the influence of the different post materials and shapes can be inferred. It can be observed that both the shape and the material had influence on the maximum stresses on that region.

Post shapes significantly altered the stress concentration on that region, although this effect was higher for different materials. Cylindrical posts introduced the lowest stress concentration level compared with the other posts for the same material, reducing it up to 37%. Similar results were observed by Henry (1977) and by Davy *et al.* (1981). Stress concentration on that region, however, was much more affected by the post material. Carbon fibre posts introduced the lowest stress concentration level (up to 145% reduction), followed by titanium and by stainless steel, for the same post shape. Assif *et al.* (1989) pointed out that a metallic post may not attend all mechanical necessities for an endodontically treated tooth. Metals are stiffer than dental tissues therefore introducing undesirable stress concentrations, which was also observed by Isidor, Ödman and Brondum (1996). The ideal post is the one which has the stiffness as close as possible to the dental tissue, thus indicating the use of composite materials to meet this task.

It is important to note, however, that the presence of the post significantly altered the stress distribution on the healthy tooth, modifying it from compressive to tensile stress (Fig. 3, Table 4). This fact can be explained by the nature of the problem. The applied load can be decoupled into its two components on the *x* and *y* direction. The *x* component generates bending on the root structure and the *y* component is responsible for axial compression in this region. The natural tooth have the root pulp chamber filled with a very soft tissue while the treated tooth has posts made of a very stiff material introduced into the root canal. The result is that the post absorbs most of the compressive loading, leaving the task of bending resistance to the adjacent dentin, thus introducing a tensile stress concentration on a region that was before in compression on the healthy tooth.

According to Cailleteau *et al.* (1992) the stress magnitude on the dentin/post interface is important because it can be associated to dentin crack initiation or even dentin fracture.

Conclusions

The results of this 2-D finite element stress analysis indicated that the use of posts for restoration substantially modifies the stress distribution of an originally healthy upper central incisor. Tensile stresses concentrated on the dentin/post interface at the palatine side of the coronal third of the root. Analysis also showed that different post shapes presented relatively small variations on the maximum tensile stresses observed, but post material played an important role. For the same post shape, stainless steel posts introduced the larger tensile stress concentration followed by titanium posts. Carbon/Bis-GMA posts presented the least level of stress concentration.

The use of posts did not significantly modify the tensile stress level on the other stress concentration region located on the dentin at the cervical region on the tooth palatine side. On this region neither the shape nor the material changed the stress concentration significantly also present on the healthy tooth.

Although the results are dependent of the mathematical model and hypothesis used, they suggest that the use of posts should be guided not only by the most adequate shape, but mainly by the most favourable material for each application, resulting in better prognostic for endodontically treated teeth.

Acknowledgments

The authors would like to thank the support given by the Brazilian sponsor agencies CNPq and FAPEMIG through research grants, and also ANSYS for allowing the use of the Research Version of their finite element code on the stress analyses performed on this study.

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