Influences of Implant and Framework Materials on Stress Distribution: A Three-Dimensional Finite Element Analysis Study

Gulcan Bahadirli, DDS, PhD¹/Suat Yilmaz, ENG, PhD²/Tobie Jones, DMD³/Deniz Sen, DDS, PhD⁴

Purpose: The aim of this study was to analyze and compare the stress distribution patterns of different implant and restorative materials in the supporting tissue and implants. Materials and Methods: Twelve different implant/bone models were created using SolidWorks 2015 software (SolidWorks Corp) and analyzed using the finite element method. Straumann Bone Level implants with zirconia abutments and single-piece Straumann PURE Ceramic implants (Institute Straumann) restored with lithium disilicate glass-ceramic and zirconia ceramic cement-retained crowns were evaluated. A 118.2-N load was applied to the coronal aspect of the buccal cusp at a 75.8-degree angle in relation to the occlusal plane. Principal stress values for cortical and trabecular bone and the equivalent von Mises stress values for implants and frameworks were calculated. Results: Zirconia (ZrO₂) implant models showed lower principal stress values than the commercially pure titanium (cpTi) and titanium-zirconium (TiZr) implant models in cortical bone. All models showed similar principal stress values in trabecular bone. Von Mises stress values at the cpTi and TiZr implants were similar; however, values observed of ZrO₂ implants were higher. TiZr implants of 3.3 mm diameter showed similar strength to 4.1-mm-diameter cpTi implants. Both zirconia and lithium disilicate glass-ceramic frameworks transferred similar von Mises stress values in the supporting tissue of implant-supported prostheses. Conclusion: Narrow-diameter TiZr implants may be preferred for patients who have insufficient bone volume without bone augmentation procedures due to the material's enhanced biomechanical properties. ZrO₂ implants may be a suitable alternative for esthetic regions. Further clinical studies are recommended to investigate the long-term performance of TiZr and ZrO₂ implants. Int J Oral Maxillofac Implants 2018;33:e117–e126. doi: 10.11607/jomi.6261

Keywords: lithium disilicate glass-ceramic, three-dimensional finite element analysis, TiZr implants, zirconia, zirconia implants

Dental implants have become the gold standard for restoring edentulous spaces; thus, ongoing research into implant and implant framework materials is imperative, striving for improved function and esthetics. It is widely known that clinical success of oral implantology is due to osseointegration of implants within the bone, the success of which depends on the patient’s health, quality of bone, bacterial contamination during implant placement, loading, implant design, material and surface characteristics, prosthesis design and material, and other biomechanical factors.¹⁻³

Due to its excellent corrosion resistance and biocompatibility, titanium (Ti) remains the choice implant material for treatment of edentulous spaces.³ The osseointegration of commercially pure titanium (cpTi) with surrounding bone underscores its clinical success in dental implant applications; however, its mechanical strength can be insufficient when smaller-diameter implants (≤ 3.5 mm) are indicated.⁴⁻⁷ For smaller-diameter implants, titanium-zirconium (TiZr) alloys are preferred because of their increased hardness and tensile strength, while maintaining the favorable corrosion resistance and biocompatibility of pure titanium.⁷

¹PhD, Department of Prosthodontics, Istanbul University Faculty of Dentistry, Fatih, Istanbul, Turkey.
²Professor, Metallurgical & Materials Engineering Department, Istanbul University -Cerrahpasa Faculty of Engineering, Avciilar, Istanbul, Turkey.
³Assistant Professor, Department of Restorative Dentistry, Oregon Health & Science University, Portland, Oregon, USA.
⁴Professor, Department of Prosthodontics, Istanbul University Faculty of Dentistry, Fatih, Istanbul, Turkey.

Correspondence to: Dr Gulcan Bahadirli, Department of Prosthodontics, Istanbul University Faculty of Dentistry, 34093 Fatih, Istanbul, Turkey. Fax: +90212 5312230. Email: gulcanpirbudak@gmail.com

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While there is no disputing the performance of both cpTi and TiZr as dental implant materials, there are esthetic concerns due to the opacity and dark coloration of these materials, which can cause the appearance of a dark shadow in the peri-implant soft tissue. This shadowing is especially prevalent in patients with a thin gingival biotype and even more so when recession is present. Ceramics have been suggested as an alternative to cpTi and TiZr alloys for dental implants because of their biocompatibility, low affinity for plaque, and improved esthetic characteristics. However, even if osseointegration is achieved, most currently available dental ceramics do not possess biomechanical properties sufficient for long-term use. Recently, the ceramic zirconia (ZrO₂) was introduced as a potential implant material. In addition to its white, tooth-like coloration, zirconia has excellent chemical and physical properties, including low corrosion potential, low thermal conductivity, high external strength (900 to 1,200 MPa), Vickers hardness (1,200), and Weibull modulus (10 to 12).

Finite element analysis (FEA) is a technique commonly used to numerically analyze stress in engineering and biomechanical fields in order to prevent the occurrence of problems associated with material failure. In implant dentistry literature, FEA studies typically focus on stress distribution as related to the implant, peri-implant bone (cortical and trabecular), and/or the restoration. Simulated forces can be applied at specific points in the implant peri-implant region and surrounding structures to analyze stress. Such modeling can aid in understanding various biomechanical factors that are important to maintaining a proper implant-bone interface. Measurements of specific interest include principal stress values such as tensile, compressive, and shear stresses and von Mises stress values. Principal stress values are especially important for brittle materials, such as bone. Bone is resistant to compressive stresses; however, it is 30% less resistant to tensile and 65% less resistant to shear stresses. The most harmful stresses affecting the bone are shear stresses. It has been reported that implant designs should be made to resist shear and tensile stresses occurring at the bone-implant interface. Von Mises stress values are defined as the beginning of deformation for ductile materials and are important for interpreting stresses occurring within implants. Failure occurs when von Mises stress values exceed the yield strength of implant materials.

Adequately controlling these factors aids in the prevention of a variety of complications including fracture of the implant, implant components, restorative materials, and resorption of the peri-implant bone. Although some research suggests biomechanical analysis in implantology to improve rehabilitation with different implant materials, literature is scarce regarding evaluation of stress distribution patterns of TiZr alloy implants in the supporting tissue and comparison of TiZr alloy with other materials. The purpose of this study was to analyze and compare the stress distribution patterns of varying implant and restorative materials in the implants and supporting tissue. The primary hypothesis was: The implant materials cpTi, TiZr alloy, and ZrO₂ will affect stress distribution patterns differentially. The second hypothesis was: Restorative materials will influence the distribution of stress in the supporting tissues differently.

### MATERIALS AND METHODS

A three-dimensional type II bone model of the posterior mandible with 2-mm cortical bone width was created for this study. In accordance with the literature, dimensions of this bone block were 24.2 mm in height, 16.3 mm in width, and 16.3 mm in thickness. Twelve different implant/bone models were created and analyzed per the Finite Element Method. The models used in this study are shown in Table 1.

<table>
<thead>
<tr>
<th>Implant diameter (mm)/Model</th>
<th>Implant materials</th>
<th>Restorative materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M1</td>
<td>cp grade IV Ti</td>
<td>ZrO₂</td>
</tr>
<tr>
<td>M2</td>
<td>cp grade IV Ti</td>
<td>Li₂Si₂O₅</td>
</tr>
<tr>
<td>M3</td>
<td>TiZr</td>
<td>ZrO₂</td>
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<tr>
<td>M4</td>
<td>TiZr</td>
<td>Li₂Si₂O₅</td>
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<tr>
<td>M5</td>
<td>ZrO₂</td>
<td>ZrO₂</td>
</tr>
<tr>
<td>M6</td>
<td>ZrO₂</td>
<td>Li₂Si₂O₅</td>
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<tr>
<td>4.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M7</td>
<td>cp grade IV Ti</td>
<td>ZrO₂</td>
</tr>
<tr>
<td>M8</td>
<td>cp grade IV Ti</td>
<td>Li₂Si₂O₅</td>
</tr>
<tr>
<td>M9</td>
<td>TiZr</td>
<td>ZrO₂</td>
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<tr>
<td>M10</td>
<td>TiZr</td>
<td>Li₂Si₂O₅</td>
</tr>
<tr>
<td>M11</td>
<td>ZrO₂</td>
<td>ZrO₂</td>
</tr>
<tr>
<td>M12</td>
<td>ZrO₂</td>
<td>Li₂Si₂O₅</td>
</tr>
</tbody>
</table>

The models used in this study are shown in Table 1.
zirconia ceramic (IPS e.max ZirCAD, Ivoclar-Vivadent). Feldspathic ceramic (IPS e.max Ceram, Ivoclar-Vivadent) was veneered onto both frameworks (Table 1). The thicknesses of IPS e.max ZirCAD and IPS e.max CAD framework models were 0.8 mm axially and 1 mm occlusal, according to manufacturer recommendations. The thickness of feldspathic ceramic veneer was 0.7 mm axially and 0.8 mm occlusally. For this study, cement thickness was considered irrelevant (Fig 1).

Implant/bone models were created using SolidWorks 2015 software (SolidWorks Corp). The models were transferred to the ANSYS 17.0 Workbench Software (Swanson Analysis Systems), which allows pre- and post-processing of finite element models, importation of geometries, mesh generation, configuration of mechanical properties and material models, and simulation of physical performance.

A finite element mesh was generated for analysis (Table 2, Fig 2). The Young’s modulus and Poisson’s ratio were determined in accordance with existing literature (Table 3). All materials were considered isotropic, linear, and homogenous.

The primary bone model was defined by establishing boundary conditions, restriction, and loading to simulate real clinical situations. The bone block was fixed in three planes on the lateral surfaces while the base was maintained as free. The bone-implant interface was assumed to have complete osseointegration. All matching surfaces between the structures of the study were simulated by direct contact, meaning that the contact avoids penetration, sliding, or movement between the surfaces. External loads equaling 114.6 N axially, 17.1 N buccal-lingually, and 23.4 N mesiodistally were applied synchronously to the coronal aspect of the buccal cusp. The combination of the loads equivocates a 118.2 N load at 75.8 degrees relative to the plane of occlusion. The load area had a 0.4-mm radius (Fig 3).

Analysis of the models was conducted at Istanbul University, Engineering Faculty, Metallurgy and Materials Department using ANSYS 17.0 Workbench 3-dimensional finite element analysis program on a computer with an Intel Core i5-4460 CPU 3.20-GHz processor with 1 TB hard disc, 16 GB RAM memory, and a Windows 10 Pro operating system.

The principal stress values for cortical and trabecular bone and the equivalent von Mises stress values for implants and frameworks were calculated to analyze the results. The unit of measurement was megapascals (MPa).

**RESULTS**

**Principal Stress Values and Distribution**

In all models, the highest principal stress values were observed around the implant neck, with compressive stress (negative values) in the distal and tensile stresses (positive values) in the mesial regions (Figs 4 to 6).

- **Cortical Bone.** The highest compressive stress value for cortical bone (~26.5 MPa) and the lowest compressive stress value (~17.3 MPa) were observed, in models M3 and M12, respectively (Fig 4). The highest tensile stress value (9.2 MPa) and the lowest tensile stress values (4.2 MPa) were observed in models M3, M11 and M12, respectively.
Table 2 Model Nodes and Elements

<table>
<thead>
<tr>
<th>Model</th>
<th>Elements</th>
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<tr>
<td>M1</td>
<td>65,257</td>
<td>112,689</td>
</tr>
<tr>
<td>M2</td>
<td>65,220</td>
<td>112,633</td>
</tr>
<tr>
<td>M3</td>
<td>65,220</td>
<td>112,633</td>
</tr>
<tr>
<td>M4</td>
<td>65,220</td>
<td>112,633</td>
</tr>
<tr>
<td>M5</td>
<td>45,627</td>
<td>77,257</td>
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<tr>
<td>M6</td>
<td>45,627</td>
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<tr>
<td>M7</td>
<td>54,113</td>
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<td>M8</td>
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<tr>
<td>M9</td>
<td>54,113</td>
<td>93,314</td>
</tr>
<tr>
<td>M10</td>
<td>54,113</td>
<td>93,314</td>
</tr>
<tr>
<td>M11</td>
<td>57,271</td>
<td>96,259</td>
</tr>
<tr>
<td>M12</td>
<td>57,271</td>
<td>96,259</td>
</tr>
</tbody>
</table>

Table 3 Mechanical Properties of Materials Used in Model

<table>
<thead>
<tr>
<th>Structures</th>
<th>Young's modulus (GPa)</th>
<th>Poisson's ratio</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cortical bone</td>
<td>13.7</td>
<td>0.30</td>
<td>19, 24, 25, 26, 27, 28, 29, 30, 31, 32</td>
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<tr>
<td>Trabecular bone</td>
<td>1.37</td>
<td>0.30</td>
<td>19, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34</td>
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<tr>
<td>cp grade IV Ti implant</td>
<td>110</td>
<td>0.35</td>
<td>25, 26, 27, 28, 30, 31, 32, 35, 36, 37</td>
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<tr>
<td>ZrO₂ implant and abutment</td>
<td>220</td>
<td>0.30</td>
<td>38</td>
</tr>
<tr>
<td>TiZr implant</td>
<td>98</td>
<td>0.25</td>
<td>Information provided by manufacturer</td>
</tr>
<tr>
<td>IPS e.max ZirCAD framework</td>
<td>220</td>
<td>0.30</td>
<td>38</td>
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<tr>
<td>IPS e.max CAD framework</td>
<td>95</td>
<td>0.23</td>
<td>38</td>
</tr>
<tr>
<td>IPS e.max Ceram Feldspathic ceramic</td>
<td>68</td>
<td>0.24</td>
<td>38</td>
</tr>
</tbody>
</table>
The ZrO$_2$ implant models displayed lower stress values than the cpTi and TiZr implant models. No significant differences in cortical bone principal stress values were found with respect to differing framework materials.

**Trabecular Bone.** The highest compressive stress value for trabecular bone (~2.6 MPa) and tensile stress value (2.1 MPa) were observed in model M1 (Fig 6). The lowest compressive (~1.9 MPa) and tensile stress values (1.5 MPa) were observed in model M8 (Fig 6). No significant differences in trabecular bone principal stress values were found with respect to differing implant or framework materials.

**Von Mises Stress Values and Distributions**

**Implant Materials.** In all models, the highest von Mises stress values were observed around the implant neck in the distal region. For implants, the highest von
Mises stress value (170.6 MPa) and the lowest von Mises stress value (66.3 MPa) were observed in models M5 and M8, respectively (Fig 7).

ZrO2 implants demonstrated higher von Mises stress values than cpTi and TiZr implants. No significant differences of implant von Mises stress values were found with respect to differing framework materials.

Ratios of von Mises stress values of implants to the yield strength of the implant materials\(^9,23,40-43\) (Table 4) are shown in Fig 8. TiZr implants of 3.3 mm diameter displayed similar strength to 4.1-mm-diameter cpTi implants. Both 4.1-mm-diameter ZrO2 and TiZr implants showed greater strength compared with cpTi implants with the same diameter.

**DISCUSSION**

Provided there is successful osseointegration, clinical success of dental implants is greatly influenced by mechanical stresses transferred from the implant to the surrounding bone. Studies indicate that implant design, in conjunction with implant and restorative...
materials, significantly affects stress distribution in bone around implants.\textsuperscript{20,44} FEA is one of the most frequently used methods to predict stress distribution where implants contact cortical and trabecular bone.\textsuperscript{16} In order to obtain reliable results, the number of elements and nodes must be 30,000 to 200,000, whereby increasing the number of elements provides more accurate analysis.\textsuperscript{45,46} However, the increase in the number of element and node points leads to prolongation of analysis. For this reason, in many studies, the number of elements and nodes has either been limited, or the number has been reduced in the areas that are outside the examined area.\textsuperscript{14,20,47} The models used in this study have an average of 56,930 elements and 97,573 node points. These numbers are well above the number of elements and nodes used in the vast majority of studies using the FEA method.\textsuperscript{48–50} Therefore, it is likely that the results of this study are closer to the actual outcome.

Additionally, modeling can cause constraints on the results of analysis in parts needing to be examined. It is possible to obtain a more detailed examination of these structures and more accurate results by increasing the number of nodes and elements of the area that is intended to be analyzed.\textsuperscript{51–53} Teixeira et al stated that the stress values and distributions occurring in the bone structures that are more than 4.2 mm away from the implant are similar, so the bone marrow models farther from this distance do not change the FEA results significantly.\textsuperscript{53} Tada et al modeled the mandibular bone in the shape of a box and stated that this practice shortened the research period, and the results obtained were more accurate. In this study, bone models were prepared to mimic the dental arch in the mandibular second molar area.\textsuperscript{54}

For this study, three-dimensional models of cortical and trabecular bone were created to analyze and compare the stress values and distribution patterns of different implant and restorative materials. Specifically compared were cpTi and TiZr implants with ZrO\textsubscript{2} abutments, and single-piece ZrO\textsubscript{2} implants restored with zirconia and lithium disilicate glass-ceramic crowns.

The primary hypothesis that the implant materials such as cpTi, TiZr alloy, and ZrO\textsubscript{2} will affect the stress distribution patterns differentially was accepted. The findings of this study indicate 3.3-mm-diameter TiZr implants display greater strength than equivalent diameter cpTi and ZrO\textsubscript{2} implants. ZrO\textsubscript{2} implants transmitted lower stress values than cpTi and TiZr implants in cortical and trabecular bone.

Brittleness is the relative inability of a material to sustain plastic deformation prior to fracture.\textsuperscript{55} It is crucial to know principal stress values for materials that are brittle, like bone, because failure occurs when tensile and compressive stresses are greater than or equal to ultimate tensile and compressive strengths, respectively.\textsuperscript{16} The results from this study indicate that the highest tensile and compressive stress values of cortical bone were found in model M3, with values of 9.24 MPa and –26.53 MPa, respectively. The highest tensile and compressive stress values of trabecular bone were found in model M1, with values of 2.06 MPa and –2.64 MPa, respectively. Values were lower than the ultimate tensile and compressive strengths of cortical and trabecular bone. The results found are in accordance with previous studies reporting that overloading of cortical bone occurs when the compressive stress values exceed 170 to 190 MPa, and tensile stress values exceed 100 to 130 MPa. Moreover, overloading of trabecular bone occurs when tensile and/or compressive stress values exceed 5 MPa.\textsuperscript{21,56}

Ductility is the ability of a material to sustain a large permanent deformation under tensile load prior to fracturing. If a material sustains tensile stress and considerable permanent deformation without rupture, it is ductile.\textsuperscript{55} The onset of deformation for ductile materials is known as von Mises stress, the values of which are important for the interpretation of stresses occurring within dental implants.\textsuperscript{16} The results of this study indicate that the highest von Mises stress values of the implant were found in model M5 at 170.55 MPa. The lowest von Mises stress value of the implant was found in model M8 as 66.25 MPa. These values were lower than the yield strength of cpTi, TiZr, and ZrO\textsubscript{2} implant materials (Table 4).

The results indicate that ZrO\textsubscript{2} implants transmit lower compressive and tensile stress values than cpTi and TiZr implants in cortical bone. Similar compressive and tensile stress values were observed in trabecular bone. Çağlar et al evaluated von Mises and principal stress values of a titanium implant and abutment, a titanium implant with a zirconium abutment, and a single-piece zirconia implant, and found that ZrO\textsubscript{2} implants transmitted lower stress values than cpTi implants in cortical bone.\textsuperscript{57} Results are congruent with those found in the present study. Kohal et al reported that ZrO\textsubscript{2} implants had similar stress distribution to cpTi implants, which was not in agreement with the results from the present study.\textsuperscript{50} This difference may be attributed to varying implant designs and stress criteria between studies.

The von Mises stress values of cpTi and TiZr implants were similar; the values observed for ZrO\textsubscript{2} implants were higher. The results support known elastic moduli of implant materials.

Plastic deformation occurs when the von Mises stress value exceeds the yield strength of the implant materials.\textsuperscript{16} The ratio of the von Mises stress values to the yield strength of the implant materials may be related to the strength of the implant material;
however, information regarding this relationship is scarce in the literature. The results from this study indicate that 3.3-mm-diameter TiZr implants show more strength than cpTi and ZrO2 implants with the same diameter. Both ZrO2 and TiZr implants with a 4.1 mm diameter displayed greater strength compared with cpTi implants of the same diameter. TiZr implants of 3.3 mm diameter demonstrated similar strength to 4.1-mm-diameter cpTi implants. Clinical studies that demonstrate success rates of different implants support the results of the present study. Barter et al reported that 20 TiZr implants were considered successful after a 2-year follow-up.58 Al-Nawas et al confirmed that bone-level TiZr implants and 3.3-mm-diameter cpTi implants display the same outcomes after 12 months.59 Andreiotelli and Kohal evaluated the fracture strength of ZrO2 implants after exposure to an artificial oral cavity and reported that all mean fracture strength values obtained were within the limits of clinical acceptance.60 The aforementioned studies indicate that the improved mechanical properties of TiZr implants may extend implant therapy to the realms of increasingly challenging clinical situations.

The second hypothesis that the restorative materials will influence the distribution of stress differently in the supporting tissue of implant-supported prostheses was not accepted. The findings of this study are similar to previous studies in which no significant differences were found in bone stress distribution with respect to the framework material.15,20,61,62 Kim et al compared the fracture load and failure mode of lithium disilicate glass-ceramic and zirconia crowns and reported that lithium disilicate glass-ceramic crowns are applicable to posterior implant-supported restorations.63 After a 2-year follow up, Fasbinder et al confirmed that lithium disilicate glass-ceramic crowns may be an effective option for all-ceramic crowns.64 Kern et al reported that lithium disilicate glass-ceramic restorations showed 5- and 10-year survival and success rates.65 According to data obtained from this study, lithium disilicate glass-ceramic restorations may be used instead of zirconia restorations for implant-supported prostheses in the premolar region. Long-term clinical data are recommended to confirm the results.

CONCLUSIONS

Within the limitations of this study, the following results were obtained.

ZrO2 implant models showed lower principal stress values than the cpTi and TiZr implant models in cortical bone. All models showed similar principal stress values in trabecular bone. Principal stress values observed in bone were lower than the ultimate tensile and compressive strengths of cortical and trabecular bone.

Von Mises stress values at the cpTi and TiZr implants were similar, whereas the highest values were observed at the ZrO2 implants. However, these values were lower than the yield strength of all implant materials.

Considering all implant models, 3.3-mm-diameter TiZr implants showed similar strength to 4.1-mm-diameter cpTi implants. Both 4.1-mm-diameter ZrO2 and TiZr implants showed higher strength compared with cpTi implants of the same diameter.

Both zirconia and lithium disilicate glass-ceramic frameworks transferred similar von Mises stress values in the supporting tissue of implant-supported prostheses.

The results from this study indicate potential clinical application, in that narrow-diameter TiZr implants may be preferred for patients who have insufficient bone volume without bone augmentation procedures due to the material’s enhanced biomechanical properties. In addition, ZrO2 implants may be a suitable alternative for esthetic regions. Further clinical studies are recommended to investigate the long-term performance of TiZr and ZrO2 implants.

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22. Scientific documentation: IPS e.max CAD INSTRUCTION FOR USE LABSIDE.