Case

Use of finite element analysis in pain perception on flat ridges with various occlusal schemes in complete dentures

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ABSTRACT
Edentulism is an oral health problem that affects the quality of life because of the loss of equilibrium in the stomatognathic system with impaired mastication. This problem can be more deteriorating in the condition of flat ridges, which increases the stress distribution in the mucosa under masticatory load. Stress distributions that exceed the pressure-pain threshold will result in poor masticatory performance, making it critical to choose the ideal occlusal scheme for such ridge conditions. However, the measurement of stress distribution in the mucosa with various occlusal schemes is challenging for *in vivo* and *in vitro* testing because of the inability to represent the complex stomatotognathic system. *In silico* testing using finite element analysis (FEA) can be the solution since the modeling simulation is acquired from CT-scan or digital designs and feasible experimental treatments. This paper discusses the use of FEA in the measurement of stress distribution in the mucosa, particularly the flat ridges to different occlusal schemes in complete dentures, and its association with pain. It is concluded that advantages of FEA in obtaining accurate modeling and testing flexibility allow the measurement of stress distribution and its association with pain on flat ridges with different occlusal schemes in complete dentures.
Keywords: edentulism, flat ridge, pressure-pain threshold, stress distribution, finite element analysis

INTRODUCTION

Edentulism is an edentulous state without natural teeth,[1,2] which if it occurs as a whole it will be called as full edentulism, the condition without any natural teeth.[2] Edentulism is seen as an irreversible condition and as a final condition of the course of oral health disease, which shows changes in physical and health conditions ranging from biomechanical, phonetic, to aesthetic appearance disorders that affect quality of life.[2,3]

Edentulism is considered as one of the most severe oral cavity problems, especially for the elderly, which impacts quality of life and makes this condidition part of a public health problem and affects primary health services.[4–7] The Basic Health Research or Riskesdas in 2018 published by the Ministry of Health of the Republic of Indonesia shows that the proportion of patients who lose their teeth and become edentulous increases with age.[5] Although in developed countries the number of edentulous sufferers is decreasing every year, the opposite is happening in developing countries.[2,8] This is because socioeconomic factors, educational background, and government policies cause most patients to feel that tooth extraction and denture insertion is a more favorable treatment option when compared to the treatments to salvage the tooth that are more complicated and higher costs.[3,8–11]

Complete denture treatment not only serves to replace the missing tooth, but also includes the supporting tissues that were lost when the tooth was extracted, in order to restore the harmonious function of the stomatognathic system. The impact of tooth loss in terms of biomechanical aspects has its own problems because the loss of supporting tissue in the form of the periodontal ligament has an impact on changes in sensory and mechanical functions that cannot be replaced by the edentulous ridge.[3] These differences will affect the patient's ability to use dentures because of the need for adaptation to mastication.[3]

The edentulous ridges that serve as support for the denture base have a much smaller surface area than the periodontal ligament in healthy teeth, moreover, the tolerance threshold and adaptation of the mucosa to accept masticatory loads are not as good as that of the periodontal ligament.[3] Additionally, the movement of the denture during functional or parafunctional movements, can cause pain or even the residual ridge to receive a load that can be destructive.[3] This condition causes the patient to limit the masticatory load by choosing foods that do not require too much mastication effort so as not to exceed the tolerance of the mucosa under the denture.[3]

This will be worsen if the area of the edentulous mucosa gets smaller due to continuous resorption, as is the case with flat ridges.[12] This smaller area of the edentulous mucosa will be even more significantly different compared to the area of the periodontal ligament in completely dentate patients, and as the result, the masticatory load in flat ridge patients will be distributed over a much smaller area.[3] This matter can cause pain as a form of mu-

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cosal response when receiving excessive pressure,[13] which can be managed by reducing the load that will be received by the ridge and reducing resistance during movement.[14] One way to achieve that is by choosing a particular occlusion scheme such as lingualized or monoplane, although there are concerns that these occlusion schemes also affect the esthetics and the masticatory performance.[14]

Given that the goal of prosthodontic treatment is not only to focus on replacing the lost structure, the denture must also be able to chew foods.[15] The patient's ability to chew can be expressed in an assessment of masticatory performance, which is measured conventionally using the sieving technique,[15,16] color-changeable chewing gum,[17] or odor intensity test.[18] However, the assessments focused on how effective the patient's ability to chew without any further assessment of why some types of food could not be crushed properly, which could be because the patient was trying to limit mastication idue to exceeding the mucosal pain threshold.[3]

Assessment of the biomechanical response of the mucosa when the denture functions result in a complex structural response, so to be able to study how the biomechanical behavior occurs, a complex stomatognathic system simulation is also needed.[19] The rapid development of digital technology allows for alternative tests other than *in vivo* and *in vitro*, simulation modeling can be carried out accurately and complex biomechanical behavior can be carried out repeatedly without any destructive process, in the form of *in silico* testing, by finite element analysis (FEA).[19–21] The use of the FEA test, especially in dentistry related to the biomechanical response of the mucosa in dentures, has been widely used since 2000, and is growing rapidly.[22]

This paper aims to discuss the use of FEA in measuring the stress distribution in the mucosa, especially the flat ridges associated with pain in complete dentures with various occlusal schemes.

LITERATURE STUDIES

Stomatognathic system

The stomatognathic system or masticatory system is a combination of joint and oral structures that are involved and work together in carrying out the functions of speech, mastication, and swallowing.[1] Speech or phonetic function in edentulous patients will affect the patient's ability to communicate which ultimately plays a role in limitations in socializing and low self-confidence.[6,7,11,23]

Swallowing function is also impaired in edentulous patients where the swallowing process is carried out by moving the tongue forward between the maxillary and mandibular ridges to create a closed space. The time required for swallowing increases in edentulous patients or in patients with unstable dentures, and this increases the risk of aspiration into the laryngeal cavity.[24,25]

In terms of mastication, the edentulous state causes the digestive process that occurs in the mouth to be disturbed, which results in the improper absorption of nutrients.[7,23,26] The edentulous patients often prefer soft foods, they usually avoid vegetables or fruits that tend to be harder, which also plays a role in increasing the risk of obesity, digestive disorders, risk of heart disease, and diabetes.[23,26]

Masticatory components

Masticatory components consist of teeth and their supporting structures, temporomandibular joints (TMJ), muscles of mastication, innervation, tongue, cheeks, and lips.[1] The masticatory function of edentulous patients is disrupted due to the missing masticatory components, which is trying to be replaced by making dentures. When a tooth is extracted, the tooth and some of its supporting structures are lost (periodontal ligament and resorption of alveolar bone), so the denture will gain support from the underlying mucosa and residual alveolar bone.[3]

Biomechanical of residual ridge support

The periodontal ligament in fully dentate patients serves as support and positional adjustment for the teeth and is also responsible for sensory perception under load, which cooperates with receptors from other components of mastication to regulate mandibular movement.[3] Loss of the periodontal ligament makes a difference in support in fully dentate patients and fully edentulous patients, which will depend on mucosal support.[3]

Mucosal elasticity causes denture instability during functional and parafunctional movements, with mastication and swallowing being the most common activities that tend to occur in a vertical direction.[3] However, movement in the lateral or oblique direction has the most damaging effect because it causes displacement of the denture so that the masticatory load is distributed unevenly over the entire supporting tissue, with the area receiving greater stress than the other areas.[3,27]

Large loads that occur continuously can cause damage to the mucosa and underlying alveolar bone, so denture base needs to be made as wide as possible and in close contact with the mucosa so that the masticatory load is distributed evenly.[3]

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Flat ridges

The support of the edentulous ridge will decrease when it gets smaller due to the resorption process that occurs progressively.[12] After one year of tooth extraction, the height of the ridge decreased by 2-3 mm in the maxilla while in the mandible there was a reduction of up to 4-5 mm.[12] However, this bone remodeling process will continue but to a lesser extent, in the mandible the reduction is about 0.1-0.2 mm per year, whereas in the maxilla it is four times less.[12] A number of studies also show that increasing age has a negative correlation with the height of the alveolar ridge.[10,28,29] this is thought to be due to the greater level of bone resorption so that it cannot be balanced by the level of bone formation.[30,31]

The consequences of ridge resorption that occur in fully edentulous patients result in reduced depth and width of the vestibule and sulcus, muscle attachment closer to the crest of the ridge, loss of vertical dimension, reduced lower facial proportions, anterior rotation of the mandible, and visual appearance to prognathic looking profile.[10,12] This condition will lead to a decrease in the area of the ridge, based on the Cawood and Howell classification regarding changes in the shape of the ridge in edentulous patients, the flat ridge condition is included in classification V with inadequate height and width of the edentulous ridge to support the prosthesis.[32]

The area of the edentulous mucosa in the maxilla ranges 42.12-46.54 cm^2 on average and 23.34-28.43 cm^2 in the mandible,[33] but due to continuous resorption, this area can be reduced to 22.96 cm^2 in the maxilla and 12.25 cm^2 in the mandible.[3] When compared to the area of the periodontal ligament in complete dentition, which is 45 cm^2 in each jaw, hence the masticatory load in completely edentulous patients will be distributed over a much smaller area.[3]

Mucosal response

The oral mucosa has sufficient physiological and mechanical capacity to not deform under stress,[34] this is because of epithelium and underlying collagen fibers.[35,36] However, when subjected to excessive pressure, injuries can occur to both soft and hard tissues, pain or discomfort, and even further bone resorption, which will affect masticatory performance when wearing dentures.[13,31,37–40]

The pressure-pain threshold (PPT) is the maximum pressure that the mucosa can accept before feeling pain.[41] This value is higher from anterior to posterior with PPT in maxillary edentulous higher than in mandible.[42] The reduced area of the edentulous mucosa will cause the masticatory load to be distributed to a smaller area and decrease the PPT value, as the result, pain will appear more easily when receiving pressure.

Occlusal schemes

The reduced area of the denture support mucosa on the flat ridge requires management by reducing the load that will be received by the ridge and reducing the resistance during movement in order to prevent pain from occurring.[14] One of the efforts that can be done is to arrange the artificial teeth in certain occlusal schemes other than bilateral balanced occlusion, in example lingualized or monoplane occlusion.[14,43]

The bilateral balanced occlusion uses anatomical elements to provide a more natural appearance and good masticatory efficiency. The lingualized occlusion uses anatomical elements in the maxilla and non-anatomical elements in the mandible so that the appearance still looks natural in the premolar area. The monoplane occlusion uses non-anatomical elements as a whole so that lateral movement reduces stress on the mucosa.[14]

The difference in shape of these elements helps in reducing the load that will be transmitted to the ridge and also minimizes resistance during movement, but the impact is reduced masticatory efficiency, less aesthetic appearance, and modifications to the elements that need to be made.[14,44,45] This will be more clearly seen if the chosen occlusal scheme is a monoplane with all non-anatomical elements.

Masticatory performance

Efforts were made from obtaining the widest possible base, close adapting dentures with mucosa, to selecting an occlusal scheme as prosthodontic efforts to obtain dentures that restore the balance of the stomatognathic system. The denture produced is intended to function in mastication, and this can be assessed by testing masticatory performance.[15] Masticatory performance is carried out to measure how small food particles are produced using standardized test conditions.[1]

The conventional technique that is often used is the comminution method which uses the test food which is crushed by mastication, and the resulting particles are then filtered using a sieving technique,[15] or the use of fuchsine beads and spectrophotometry, or silicone cubes with multiple sieves.[16] In addition, there is also a mixing ability method that uses a special test food in the form of chewing gum with two colors, the patient is asked to chew and ob-

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serve the color change in the gum,[17] or with an aroma sensor that uses chewing gum with a special aroma that will be measured after the completion of mastication using an odor sensor.[18]

Finite element analysis (FEA)

The FEA is a numerical method to get a solution to a problem accurately with modelling simulations for later analysis.[20,21] This method was originally developed and used in engineering to be a solution to complex physics and engineering problems, due to a series of very complicated steps. The development of FEA allows modelling construction to be carried out quickly and effectively, thus playing an important role in the engineering field.[22]

The use of FEA in the medical field has become a testing tool that has developed significantly, especially the use of biomechanical analysis on living things, because it is non-invasive and easy to repeat without the need for duplication.[46] Furthermore, the modelling and treatment can be freely defined as desired, various elements can also be combined, the test process is run in one program, and the resulting model also has identical conditions to the original.[20]

Developments in the field of radiography such as CT and MRI have made FEA popular in dentistry, because it can accurately model bone geometry, in terms of quality, quantity, and shape.[46,47] The use of FEA in dentistry, for example the assessment in implants.[47-49] obturator,[50] restoration,[51] periodontal ligament,[52,53] and trauma and fracture.[54,55]

DISCUSSION

Resorption that occurs at the edentulous ridge is a consequence of tooth extraction and long-term use of dentures.[31,56] A systematic review conducted by Pham *et al*[56] in a number of studies that measured the rate of resorption in the posterior mandible of patients wearing complete dentures, it was found that the average resorption in the posterior mandible ranged 0.01-2.4 mm per year. This figure has a very large variation and is different from that stated by Laing and Zarb[12] stated that this resorption ranged 0.1-0.2 mm per year. This difference is thought to be due to the factor of occlusal scheme used, of which only seven studies used the bilateteral balanced occlusion.

A study by Alsaggaf and Fenlon[40] even found that patients who wore dentures for more than 5 years experienced significant ridge resorption when compared to the group that did not use dentures. This is contrary to what is stated in Wolf's Law, that the edentulous crest will atrophy if it is not used.[57] The author believes that there are other factors that play a role so that resorption in denture wearers is more significant, one of which is the possibility that the load distributed by the denture is uneven so that it exceeds the tolerance threshold of the underlying mucosa.

The mandibular rim gets its blood supply from the periosteal plexus vessels which are susceptible to disruption when exposed to pressure, which can trigger pain and discomfort. If this pressure continues, inflammatory cells will be involved which causes a hydrostatic pressure that exceeds the capillary pressure. Additionally, the supply of nutrients will be inhibited and result in further progressive resorption.[34]

The same thing was also expressed by Joanne *et al*[36] in their experimental study, that when receiving pressure, the connective tissue under the epithelium will experience changes first with collagen sloughing, which has an impact on reducing tissue resilience and lowering the PPT value.

Kondo *et al*[31] and Tanaka *et al,*[58] in their study of the biomechanical response of the mucosa under dentures, concluded that pain can occur when the mucosa under the denture receives an unbalanced load that exceeds the mucosal threshold, which if it continues will be followed by a resorption process.

The concept of occlusion is still an interesting discussion regarding prosthodontic efforts to produce stable dentures. Bhambhani *et al*[59] in their systematic review stated that in the BBO, the deflective contact of the anatomical elements can cause the denture to become unstable. The same thing was also stated in a randomized clinical trial study conducted by Shirani *et al,*[60] patients with BBO dentures tend to avoid some foods that cause discomfort due to frequent denture instability, although in the assessment of mastication efficiency there was no difference compared to other occlusal schemes.

The selection of the lingualized occlusion is also a consideration, especially in inadequate ridge conditions such as flat ridge, with consideration of reducing interferences during lateral movement with a better aesthetic appearance than the monoplane occlusion which is said to be an occlusal scheme that does not provide special benefits.[45,59] Although according to an in vitro study conducted by Madalli *et al,*[61] monoplane occlusion shows the smallest pressure distribution when compared to other occlusal schemes.

A randomized clinical trial study by Sutton *et al*[62] concluded that the lingualized occlusion was significantly superior in reducing mucosal pain when compared to the monoplane occlusion, whereas

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when compared with the BBO, the results were not significantly different.

Studies related to the comparison of various occlusal schemes in denture wearers in several studies,[45,60,62] were carried out based on mastication efficiency or masticatory performance which were assessed subjectively by patients when using dentures and without using standardized test foods. In addition, the patient's inability to destroy food due to the patient's low resistance,[17] this can be expected due to the load being received that exceeds the mucosal tolerance threshold, which cannot be detected by assessing the masticatory performance. Other studies conducted by *in vitro,*[61,63,64] were carried out directly on dentures, but the modeling of the edentulous ridges could not represent the complex original condition, so it was not adequate to study the stress distribution in the oral cavity structure.

In addition to *in vivo* and *in vitro*, assessment of dentures and how the biomechanical response of the underlying mucosa *in silico* using FEA has been carried out since 2000.[27,65–71] The simulation modeling can be obtained from scanning or digital designing (

Figure 1) then the testing will be run in a specific program such as ANSYS. The results and measurements can be observed in the form of stress distribution on the edentulous mucosa under the denture which shown in distinctive colors (

Figure 2).

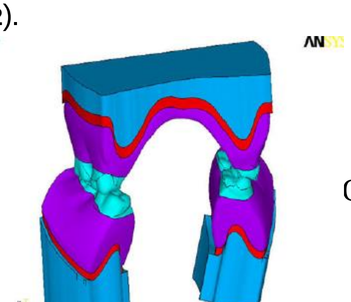

Figure 1 Simulation modeling.[66]

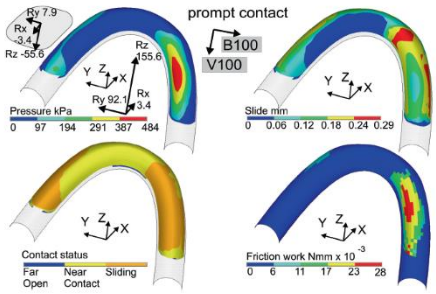

Figure 2 Stress distribution observation.[27]

Takayama *et al*[65] conducted a FEA study on mandibular dentures using anatomical factors with a load of 1 kgf (9.8 N) directed at the anterior, posterior, and balancing facets to observe the displacement of the denture. Displacement was observed to be greatest with the load directed at the balancing facet, indicating that there was premature contact occurring on the non-working side. Disadvantages in this study were the modeling was carried out by simplification of the digitally designed for both the denture and the gingival mucosa, and the given load did not represent the average masticatory load of denture wearers (50-100 N).[71,72]

Chowdhary et al[73] assessed the pattern of stress distribution with FEA on the mucosa under the denture base using 33º, 20º, and 0º factors. The cross section of the denture is made in graphic form and normal bone contours are obtained from CT results, with a load of 50 N. The result is that the 33º factor shows the greatest stress, followed by 20º and 0º. The drawback in this study is the use of 2D FEA testing so that the resulting stress distribution is only assessed at a certain point which does not necessarily receive the greatest load when functioning.

Barão *et al* [67] compared the stress distribution with FEA in the use of conventional dentures with implant-supported overdentures with various types of attachments with a load applied of 100 N to the incisal surfaces. As a result, the implant-supported overdenture received a greater load than conventional dentures. The drawback of this study is that the modeling design was made with simplification of the design and only focused on the anterior area.

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Sadr et al[68] compared the stress distribution with FEA on mandibular denture with flat ridge with and without soft-liner with a load of 50-80 N. The results showed that the use of soft-liner showed an increase in stress of 18.5-30% compared to that without soft-liner. The idea of adding soft-liner on the intaglio surface of the denture apparently did not provide cushioning effect as expected to reduce the stress received by the underlying mucosa.

Mankani *et al* [66] compared how the shape of the posterior elements with inclinations of 0º, 20º, and 33º produced different stress distributions in the tissues under complete dentures when subjectted to a masticatory load of 100N in the vertical direction. The results show that the inclination of 20º and 33º produces a higher stress distribution value than 0º, while between 20º and 33º there is no significant difference. This is estimated because different inclinations will cause changes in the direcrection of the load and the greater the inclination, the wider the contact area with the antagonist will decrease. However, this study does not include the oblique load direction variable as a representation of lateral movement, even though this movement is the most susceptible to causing disturbances to denture retention and stabilization.

Żmudzki et al[71] conducted a FEA study on the stress distribution of dentures with knife edges with a load of 100 N applied in the vertical and oblique directions. The results obtained show that the load distribution when receiving a vertical load reaches 252 kPa with a slight shift, but when receiving an oblique load this figure reaches up to 3 MPa with a shift of 1 mm. The authors compared these results with the assumption of an average PPT of 630 kPa (300-1500 kPa), thus exceeding the pain threshold fivefold, and suggested reducing the occlusal load to 30 N alone, which is insufficient for chewing food with a large size. The drawback in this study is no further information regarding relief on knife edge alveolar ridge, which is commonly made before fabricating the denture base.

Żmudzki et al[27] conducted a FEA study on stress distribution in mandibular dentures with convex ridges with a load of 100 N in the vertical and oblique directions with direct contact and delayed contact on the non-working side. As a result, the direction of the oblique load provides greater stress distribution and greater displacement, especially on the nonworking side with delayed contact. Disadvantages of this study are the delayed contact on the non-working side usually occur on unbalanced occlusion, which is avoided in complete denture and no other occlusal scheme was included in the study.

It is concluded that the management of edentulous cases, especially the flat ridge condition, requires a deeper understanding of how the occlusal scheme can play a role in maximizing the patient's masticatory performance while maintaining the condition of the mucosa of the ridge and the underlying alveolar bone from pain and further resorption. The use of FEA can help describing how the stress distribution received by the mucosa under the denture base is more accurate to carry out further analysis related to pain and the possible risk of resorption that can occur, especially if the modeling simulation can be carried out under conditions that are as similar as possible to the original condition. It is suggested that a number of studies related to the use of FEA in assessing the stress distribution in the mucosa under dentures have focused more on normal ridge conditions and bilateral balanced occlusion, so that more studies are needed regarding flat ridge conditions with various occlusal concepts, so that it can be applied in a theoretical and clinical scopes.

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