FINITE ELEMENT APPLICATIONS IN DENTAL IMPLANTOLOGY

H. GUAN[1], Y. C. LOO[2], and R. C. VAN STADEN[3]

ABSTRACT: The modern dental implant is a biocompatible titanium device surgically placed into the jawbone to support a prosthetic tooth crown in order to replace missing teeth. Although implants exhibit excellent long-term retention rates (roughly 95% after 5 years), there are significantly more failures in areas where bone quality and density are low, resulting in poor patient outcomes and costing an estimated $AUD15 million per year in Australia. Most failures arise from poor clinical technique and inadequate understanding of the potentially damaging stress characteristics during implant placement and function.

This long-term innovative research aims to develop a comprehensive Finite Element Analysis (FEA) procedure to evaluate the performance of the implant-bone system during implantation, as well as the healing, remodelling and maintenance phases of osseointegration. Once these fundamental data are collected, a 'treatment planning database' aimed at optimising patient-specific treatment outcomes will be developed which helps match implants (with specific design features) with the unique characteristics of the patient's bone at the recipient site. This research when fully completed will advance the fundamental understanding of the forces at play during implant placement, healing and function. This would lead to improvements of both clinical technique and treatment planning, ultimately resulting in superior clinical outcome and cost savings.

Summarised herein are the research tasks completed to date. They include the evaluation of the stress distributions within: (1) the mandible as influenced by dental implant and bone parameters; (2) the implant with various implant wall thicknesses; (3) the mandible as influenced by Nobel Biocare, 3i and Neoss implant thread designs; (4) the crown for two abutment-crown connection systems; and (5) the mandible during a step-wise implant insertion process. For each of the five research tasks the implant-bone system is analysed using Strand7 FEA System. The analysis results are obtained in some detail and relevant conclusions drawn.

KEYWORDS: Dental implantology, implant-bone system, finite element technique.

1. INTRODUCTION

Development of an ideal substitute for missing teeth has been a major aim of dental practitioners for millennia [1]. Dental implants are biocompatible screw-like titanium 'fixtures' that are surgically placed into the mandible or maxilla to replace missing teeth. The mechanism by which an implant is bio-mechanically accepted by the jawbone is called osseointegration [2,3]. Stimulus of the bone through applied stresses has been well documented to influence the success or failure of an implant [4,5].

Research presented in this paper comprises five tasks in an attempt to fill the knowledge gaps in current literature. Many researchers [6-13] have recognised that the implant dimensions influence the stress characteristics within the jawbone. Some indicated that the geometry has little or no effect on the success of implantation [8,10], while others concluded that an implant diameter of between 3.6 and 4.2mm produces the highest success rate [6]. Existing research publications mainly focus on the impact of a single

---

[1] *Senior Lecturer, Griffith School of Engineering, Griffith University Gold Coast Campus, Queensland 4222, Australia.*

[2] *Foundation Professor of Civil Engineering and Director, Internationalisation and Professional Liaison, Science, Environment, Engineering and Technology Group, Griffith University.*

[3] *PhD Student, Griffith School of Engineering, Griffith University.*

implant or bone parameter. No work to date has dealt with the stress characteristics within the jawbone due to a combined variation of implant geometry and bone properties. This leads to the investigation as outlined in research Task 1.

The mechanical failure of the implant has been extensively studied in terms of implant fatigue [14,15], implant fractures, veneering resin/ceramic fractures and other problems with mechanical retention [16-18]. However, specific failure due to implant wall thickness as a result of various implant diameters has not been well documented, which constitutes the work of Task 2.

The implant thread design has been studied for its influence on the stress distribution within the jawbone [19,20] and the load transfer characteristics. In Task 3 the stress characteristics within the bone are discussed for various thread designs (Nobel Biocare, 3i and Neoss implant systems [21-23]) under the combination of masticatory force and abutment preload. Several studies [24-26] have evaluated the effectiveness of implant connection to its abutment (either internal or external connections). Task 4 aims to evaluate and compare the stress characteristics within the crown for Neoss (with an internal connection) and 3i (with an external connection) implant systems.

During implantation, large stresses occur due to the torque applied in the process and the fact that the implant is cutting into the bone. As such, the stress condition in the bone continues to change during the entire insertion process. This phenomenon has not been researched adequately thereby leading to a simplified step-wise analysis of insertion process (Task 5).

The aforementioned tasks demonstrate that an in-depth understanding of implant related problems, in particular those associated with implant design and insertion technique, merits further and rigorous investigation. It is anticipated that the research outcome will benefit dentistry by providing an improved fundamental understanding of the implant-bone system at various stages of implantation.

2. METHODOLOGY

The five research tasks are arranged with the intention that each task advances on the preceding one in terms of modelling complexity. Task 1 deals with a two-dimensional (2D) modelling without implant components (i.e. abutment, abutment screw and crown). Tasks 2 and 3 advance from Task 1 by incorporating the implant components into the modelling. These two tasks also incorporate a temperature sensitive element, functioning throughout the abutment screw as a result of the applied preload (or torque). Task 4 advances further with the introduction of three-dimensional (3D) modelling. Based on the knowledge gained from all previous tasks, the implantation process is successfully modelled in Task 5 in a 3D step-wise manner.

For Tasks 1-3 and 5 data acquisition for the bone dimensions are based on Computed Tomography (CT) scanned images. The different types of bone, i.e. cancellous and cortical, are distinguished and the boundaries are identified in order to assign different material properties within the finite element model. Note that the CT technique is also used for data acquisition of the crown in Task 4.

Figures 1, 2, 5 and 7 show details of the modelling (including the loading and restraint conditions) along with the detailed variables considered for each task. Note that the implant system based on that of Neoss [24] is used throughout all tasks with the addition of Nobel Biocare and 3i for Task 3, and 3i for Task 4. The material behaviour of bone considered in Tasks 1-4 are assumed to be linear and elastic, whereas non-linear and elastic-plastic behaviour is considered in Task 5. Note that all materials are assumed to be homogeneous in all the tasks. Note also that the material properties used for the implant components, as shown in Table 1, remain unchanged for all the tasks. Figure 1 details the material properties of bone used for Task 1, and Table 1 for Tasks 2-5. For all the research tasks the implant-bone system is analysed using Strand7 [28] Finite Element Analysis (FEA) System.

Table 1 Material properties

Component	Description	Young's modulus, E (GPa)	Poisson's ratio, v	Density, ρ (g/cm³)
Implant, abutment, washer	Titanium (grade 4)	105	0.37	4.51
Abutment screw	Gold (prec. alloy)	93	0.3	16.3
Crown	Zirconia (Y-TZP)	172	0.33	6.05
Cancellous bone		1	0.3	0.74
Cortical bone	1.3mm thickness	13.7	0.35	2.17

3.   RESEARCH TASK 1

Guan et al [28] investigated the stress characteristics in the bone when various combinations of bone and implant parameters are considered (Figure 1). In general, it was found that an increase in length (L) reduces the stress, within both cancellous and cortical bone, for a wider range of parameters as compared to increasing the diameter (D). Decreasing the cortical bone thickness (T_{cor}) leads to the cortical bone supporting less load which in turn results in a slight increase in the stress magnitude in the cancellous bone. When Young's modulus of the cancellous bone (E_{can}) increases the stress magnitude also increases due to the cancellous being able to

Loading Conditions
Horizontal loading, F_H = 25 - 250N
Vertical loading, F_V = 50 - 500N
Moment, M = 162.5 - 1625Nmm

Fixed constraint

Dental implant
Diameter, D = 3.5, 4.0, 4.5, 5.5mm
Length, L = 7, 9, 11, 13, 15mm

Taper

Cancellous bone
Young's modulus, E_{can} = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14GPa

Cortical bone
Thickness, T_{cor} = 0.3, 0.6, 0.9, 1.2, 1.5, 1.8, 2.1mm
Young's modulus, E_{cor} = 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20GPa
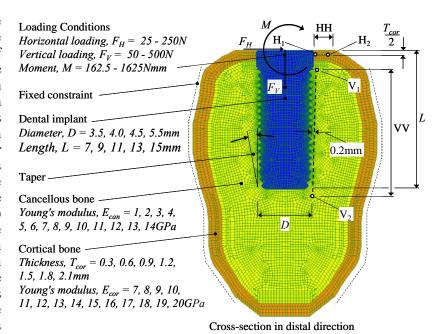
Cross-section in distal direction

Figure 1. Finite element model of the dental implant and mandible

support more load. Decreasing Young's modulus of the cortical bone (E_{cor}) increases the stress within the cancellous bone because it has to support a greater portion of the load. On the other hand, the stress within the cortical bone increases as E_{cor} increases, because the cortical bone offers more resistance to the load.

As a logical extension, the implant, bone and loading parameters viz D, L, T_{cor}, E_{can}, E_{cor}, F_H, F_V, and M (see Figure 1) are ranked in terms of the stress variations. They are represented by the average differences (AD) between the stresses when a single parameter is set to its minimum and maximum values while all other parameters are set to their mean values. As indicated in Figure 1, the von Mises stresses along the lines VV for cancellous bone and HH for cortical bone are measured for all possible parameter combinations. Note that the distance of VV away from the thread tip is fixed at 0.2mm (see Figure 1) in an attempt to capture the stresses at the most critical location [29]. The differences in stress at distances 1, 4.5, 9mm from V_1 and 0.2, 0.6, 1mm from H_1 along the lines VV and HH respectively, are given in Table 2. Note in Table 2 that F-M represents the load combination F_H, F_V and M.

When considering the average differences (AD) in stresses along the line VV, the ranking order is F-M>L>E_{can}>T_{cor}>D>E_{cor} where ">" indicates greater difference in stress than the next parameter. The applied loading (F-M) has a more significant influence on the stress difference, within the cancellous bone, than all other parameters. Young's modulus of the cortical bone (E_{cor}) exhibits the lowest AD, which is especially evident at a distance of 1mm along the line VV. The ranking order for the AD in stress along the line HH is F-M>E_{can}>E_{cor}>T_{cor}>D>L. As found for cancellous bone, F-M is still more influential than all parameters on the stress difference within the cortical bone.

Table 2 von Mises stress (MPa) in cancellous and cortical bone (stress along the line HH shown in brackets)

VV/HH (mm)	D	L	T_{cor}	E_{can}	E_{cor}	F-M
1 / 0.2	2.02 (16.86)	16.82 (21.92)	4.25 (53.29)	26.12 (66.80)	1.85 (52.98)	41.70 (87.80)
4.5 / 0.6	3.34 (25.70)	18.93 (18.19)	4.26 (16.24)	6.44 (81.33)	1.87 (55.80)	27.95 (83.27)
9 / 1	3.64 (22.27)	20.33 (15.17)	8.70 (3.06)	6.14 (52.02)	2.81 (41.58)	30.15 (69.66)
AD	3.00 (21.61)	18.69 (18.43)	5.74 (24.20)	12.90 (66.72)	2.18 (50.12)	33.27 (80.24)

In general, it is found that the implant length has a more significant influence on the stress difference, in the cancellous bone, than the diameter. However, the diameter is more influential on the stress difference within the cortical bone. Compared to all the other parameters, the applied loading has a more substantial influence on the stress difference in both cancellous and cortical bone. Young's modulus of the cortical bone and the implant length are found to be least influential in the cancellous and cortical bone respectively.

4.   RESEARCH TASK 2

The loading transferred to the bone is significantly influenced by the design of an implant. From a bioengineering perspective, an important criterion in designing an implant is to have a geometry that can minimise the peak bone stress caused by an extensive range of loading. van Staden et al [30] evaluated four implant diameters for their effect on the stress characteristics within the implant wall under varied masticatory forces, F_M, and abutment screw preloads, F_P (Figure 2). The F_M is found to play a more significant role than F_P on the probability of implant fracture. For this reason only the representative results of varying F_M (at 200, 500 and 1000N) are discussed herein. Note that F_P is set at its average value, i.e. 587.44N. As indicated in Figure 2, the stresses along the lines $VV_{1\text{-}2}$, $VV_{2\text{-}3}$ and $VV_{3\text{-}4}$ are measured for all possible combinations of diameters and loadings.
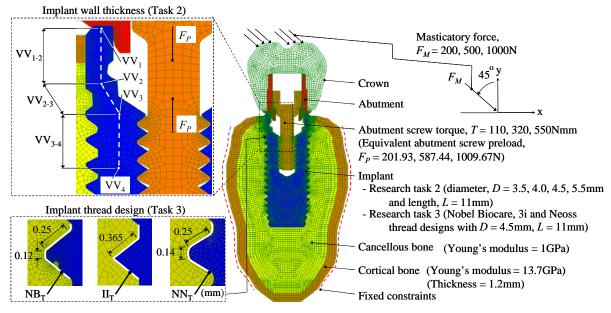
Figure 2. Finite element model of implant, components, implant-bone interface and bone
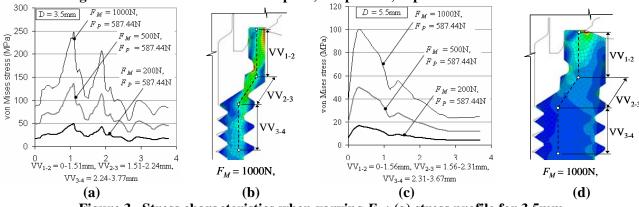

**Figure 3. Stress characteristics when varying F_M: (a) stress profile for 3.5mm,
(b) stress contour for 3.5mm, (c) stress profile for 5.5mm, (d) stress contour for 5.5mm**

Figure 3 shows that with increasing F_M, the stresses also increase proportionally, because the system being analysed is linear and elastic. As expected the 3.5mm diameter implant shows higher stresses within the implant wall than the 5.5mm counterpart. The 3.5mm implant also induces stress peaks along the lines $VV_{1\text{-}2}$ and $VV_{2\text{-}3}$ (see Figures 3 a) and b)). This is because the implant wall thickness for the 3.5mm implant is significantly reduced in the region corresponding to $VV_{2\text{-}3}$, thereby causing a stress concentration. In the study by van Staden et al [30] the 4.0 and 4.5mm diameter implants have similar stress distribution characteristics. However the stresses are lower in magnitude at $VV_{1\text{-}2}$, $VV_{2\text{-}3}$ and $VV_{3\text{-}4}$ as compared to the 3.5mm implant because of their larger wall thicknesses. The 5.5mm implant displays greatly reduced stresses at all locations as evident in Figures 3 c) and d), with peak stresses occurring close to the point VV_1 (see Figure 2).

5. RESEARCH TASK 3

Guan et al [31] evaluated the stress characteristics within the cancellous bone for three implant thread designs (Nobel Biocare, 3i and Neoss) with varied masticatory forces (F_M) and abutment screw preloads (F_P) - see Figure 2. Note that for an exclusive comparison of the three outer thread designs, the crown, the abutment and abutment screw as well as the inner implant thread design of the Nobel Biocare and 3i implants are kept identical to the Neoss system. The implant diameter is 4.5mm, the length is 11mm and the cortical bone thickness is 1.2mm. The detailed thread configurations and dimensions are shown in Figure 2.

The von Mises stresses was evaluated by Guan et al [31] at three regions of the thread, i.e. top (T), middle (M) and bottom (B) for the three different thread designs viz Nobel Biocare (NB), 3i (II) and Neoss (NN). However, in this study only the top thread is considered under varying F_P, because the most evident stress characteristics are identified at this location. As shown in Figure 2, the stresses along the lines, NB_T, II_T and NN_T are measured for the top region of the thread. These lines which are located within the cancellous bone, closely follow the thread profile. Such locations are considered by clinicians to be critical for examining the stress levels in the cancellous bone.
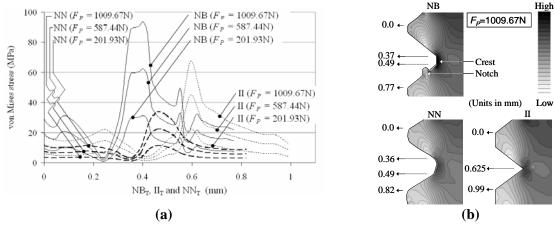

(a)   (b)

Figure 4. Stress characteristics in cancellous bone within top region of thread: (a) stress profile, (b) stress contour

The distribution of stresses along the lines NB_T, II_T and NN_T are shown in Figure 4. Note in Figure 4 b) that the numbers on the left hand side of each tread profile indicate the distances (in mm) from the starting point (0.0mm) along the NB_T, II_T and NN_T lines. As predicted, when F_P is increased, the stresses also increase proportionally for the three thread designs. This is again because the system is linear elastic. Due to different geometry of the thread, the maximum stress of the Nobel Biocare design is found to be the highest among the three designs and that of the Neoss design, the lowest. The Nobel Biocare design produces a global stress peak at the location close to the implant crest (see Figure 4 b)). Also noticeable are two local stress peaks at the locations close to the corners of the notch. The 3i and Neoss designs both show a stress peak near the implant crest. All these stress peaks are due to the abrupt change in geometry.

Overall the Neoss thread design yields a more favourable stress profile within the cancellous bone than the Nobel Biocare and 3i designs. This is under the condition that the inner thread design and the crown–abutment components are identical to the Neoss system for the three different outer thread designs. Compared to the Neoss's more smoothed-out thread profile, both the Nobel Biocare and 3i designs have more abrupt changes in geometry, which results in higher stresses. This is particularly true for the Nobel Biocare design where a notch is present. Although the existence of the notch helps to promote osseointegration, it inevitably produces undesirable stresses.

6. RESEARCH TASK 4

An implant may be connected to its abutment by either internal or external connections (Figure 5 a)). With external connections, a classic example of which is the external hex where the washer together with the crown is fitted onto the implant before the abutment screw is tightened. The tightening process creates severe compressive stress between the screw and crown which can cause micro-

fracture within the crown. This can cause further loosening of the abutment screw under masticatory forces, in which case the abutment must be repaired.
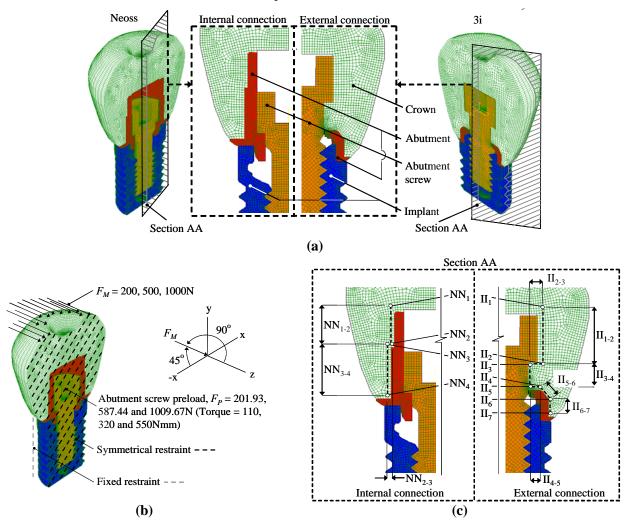

Figure 5. Finite element model of internal and external-hex systems: (a) implant systems, (b) loading and restraint conditions, (c) locations for stress measuring

The internal and external-hex connections of the Neoss (NN) and 3i (II) implant systems are compared through 3D FEA (van Staden et al [32]) under varying F_M and F_P. It is found that F_P is more influential than F_M, on the distribution of von Mises stresses in the crown for both the internal and external-hex systems. Therefore, only the stress characteristics influenced by F_P are presented herein with a constant average value of $F_M = 500N$. Detailed loading and restraint conditions are shown in Figure 5 b). Figure 5 also presents the locations for stress measurement for both Neoss and 3i systems. For the Neoss system, NN_{1-2}, NN_{2-3} and NN_{3-4} cover lengths 0-1.76mm, 1.76-1.87mm and 1.87-3.96mm, respectively. For the 3i system, II_{1-2}, II_{2-3}, II_{3-4}, II_{4-5}, II_{5-6} and II_{6-7} represent lengths 0-2.38mm, 2.38-2.78mm, 2.78-3.67mm, 3.67-4.06mm, 4.06-4.65mm and 4.65-5.27mm, respectively.

The stress profiles along the lines NN and II for all values of F_P are shown in Figures 6 a) and c). The corresponding stress contours under the maximum F_P are displayed in Figures 3 b) and d). When F_P is increased the stresses along the line NN also increase, showing two peaks along the line NN_{3-4}, as evident in Figure 6 a). The larger of these two peaks occurs at a distance of approximately 3.8mm from NN_1. This stress peak, as identified in Figure 6 b), is caused by the sharp corner and sudden change in abutment screw geometry at that point. Elevated stresses are identified at the beginning of the line II_{3-4} (Figures 6 c) and d)), which is also caused by the sharp corner at that point. The overall volume of the crown in the 3i system exceeds that of the Neoss system (see Figure 5 a)), which is expected to provide greater resistance to the abutment screw preload. However, due to the existence of high strength titanium abutment in the

Neoss system, the maximum stresses thereby induced are slightly lower than those of the 3i system. This is illustrated in Figures 6 a) and c).

7.   RESEARCH TASK 5

The objective of the study by van Staden et al [33] was to replicate the implantation process using a simplified yet efficient modelling approach. A series of finite element models was constructed and simulated to replicate the implantation process in a step-wise manner. Each model differs from the preceding one in that the implant is inserted 1mm deeper into the jawbone. As the implant is 11mm long, there are eleven different analyses to be conducted. Shown in Figures 7 and 8 are the details of the time dependent torque that is positioned at the top of the implant. Note that the torque is replicated by applying four concentrated tangential forces, F. Figure 7 also shows the fixed constraints on the side faces in the distal direction. This section provides a brief summary of the von Mises stress distributions within the cancellous and cortical bone at mid insertion depth (3-7mm) which correspond to 8.5-23 seconds where the torque is at the level of 450Nmm (Figure 8).

Unlike Tasks 1-4, non-linear material behaviour is assumed for both cancellous and cortical bone, as suggested by Burstein et al [34] where the yield and fracture stresses are respectively 35 and 40MPa for the cancellous bone, and 180 and 190MPa for the cortical bone. In the analysis, the thickness of the blood and bone fragments is assumed to be 0.5mm filling around the implant threads (Figure 9). Note that at each insertion stage, the bottom two threads of the implant cut the bone so that the remaining upper threads come in contact with the blood and bone interface.
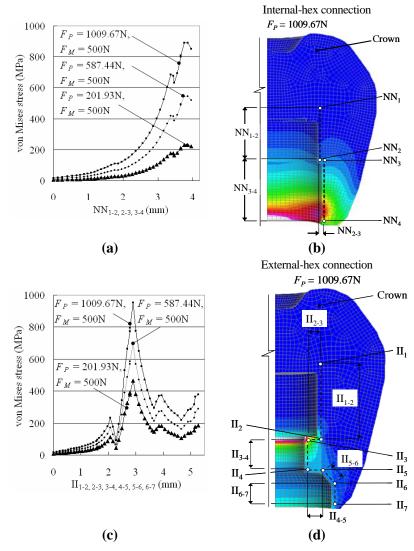

Figure 6. Stress characteristics when varying F_P: (a) stress profile for internal connection (NN), (b) stress contour for internal connection (NN), (c) stress profile for external connection (II), (d) stress contour for external connection (II)
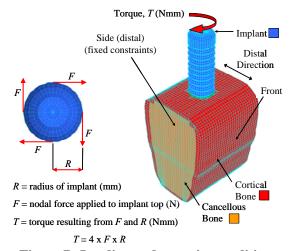

Figure 7. Loading and restraint conditions

In the analysis, the stresses are measured along the lines VV for the cancellous bone and HH for the cortical bone (Figure 9). The stress distributions within the cancellous and cortical bone, for time steps 8.5 to 23 seconds (3-7mm insertion depth) are shown together in Figures 10 a) and b).

Figure 10 a) shows that the stress profile and contour within the cancellous bone for insertion depths 3-7mm. At these depths a significant increase in magnitude is evident when compared to the previous insertion stages of 0.5 and 1mm. This is because for insertion depths of 2-11mm the implant threads are in contact with the cancellous bone. In addition, the stress peaks just below the implant neck along the line VV move down as the insertion depth increases (Figure 10 a), van Staden et al [33]).

Figure 8. Torque vs. time during implantation

Figure 10 b) shows the stress profile and contour within the cortical bone. The characteristics of the stress profile for insertion depths 3-7mm differ from the previous insertion stages (0.5-1mm), because in the initial stages the implant is in contact with the cortical bone only. For the 2mm insertion depth the stress profile is more comparable to that of insertion depths 3-7mm because there is a blood and bone interface between the implant and the cortical bone. The stress profile remains almost unchanged until the final insertion stage. However the stress level increases with the insertion
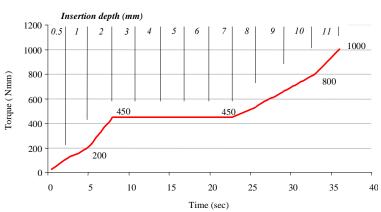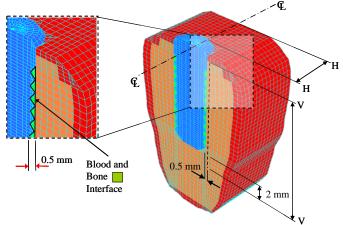

Figure 9. Stress profile measuring (dashed lines indicate the location) and location of fragments of blood and bone

depth. Note that during the entire insertion process, the maximum stresses always occur at around the implant neck. Note also that such maximum stresses do not exceed the yield stresses of 35 and 180MPa respectively for the cancellous and cortical bone.
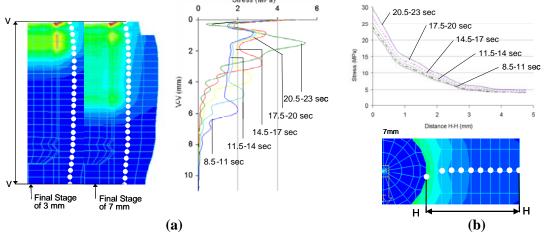

(a)   (b)

Figure 10. Stress characteristics at the intermediate insertion stages within: (a) cancellous bone, (b) cortical bone

The stress characteristics examined in this research task offered some insight into the behaviour of the cancellous and cortical bone during the implantation process. Important factors to consider for a successful implantation are the optimum insertion torque and the set time periods for each level of torque applied. It is believed that the outcome of this study will assist the clinician to perform a patient specific implant treatment in a more quality-controlled manner.

8. CONCLUDING REMARKS

The stress characteristics of the implant-bone system during and after implantation are investigated through five research tasks. The tasks cover a wide range of critically important factors for implantation including combined geometric and material variables of implant and bone, implant diameters (resulting in different wall thicknesses), implant thread designs, abutment-crown connections as well as implant insertion process. The fundamental understanding achieved in this study will help to develop a 'treatment planning database' in the future for improving selection of patient specific implant design and treatment procedures. This in turn will increase the quality of clinical techniques and outcomes.

ACKNOWLEDGEMENTS

REFERENCES

1. Irish, J. D., "A 5,500 year old artificial human tooth from Egypt: a historical note," *The International Journal of Oral & Maxillofacial Implants*, Vol. 19, No. 5, 2004, pp. 645-647.
2. Branemark, P. I., Adell, R., Breine, U., Hansson, B. O., Lindstrom, J., and Ohlsson, A., "Intra-osseous anchorage of dental prostheses. I. Experimental studies," *Scandinavian Journal of Plastic and Reconstructive Surgery*, Vol. 3, No. 2, 1969, pp. 81-100.
3. Branemark, P. I., Hansson, B. O., Adell, R., Breine, U., Lindstrom, J., Hallen, O., and Ohman, A., "Osseointegrated implants in the treatment of the edentulous jaw. Experience from a 10-year period," *Scandinavian Journal of Plastic and Reconstructive Surgery*, Vol. 16, 1977, pp. 1-132.
4. Mellal, A., Wiskott, H. W., Botsis, J., Scherrer, S. S., and Belser, U. C., "Stimulating effect of implant loading on surrounding bone. Comparison of three numerical models and validation by in vivo data," *Clinical Oral Implants Research,* Vol. 15, No. 2, 2004, pp. 239-248.
5. Carter, D. R., Orr, T. E., Fyhrie, D. P., and Schurman, D. J., "Influences of mechanical stress on prenatal and postnatal skeletal development," *Clinical Orthopaedics and Related Research,* Vol. 219, 1987, pp. 237-250.
6. Himmlova, L., Dostalova, T., Kacovsky, A., and Konvickova, S., "Influence of implant length and diameter on stress distribution: a finite element analysis," *The Journal of Prosthetic Dentistry,* Vol. 91, No. 1, 2004, pp. 20-25.
7. Plikçiolu, H., and Akça, K., "Comparative evaluation of the effect of diameter, length and number of implants supporting three-unit fixed partial prostheses on stress distribution in the bone," *Journal of Dentistry,* Vol. 30, No. 1, 2002, pp. 41-46.
8. Pierrisnard, L., Renouard, F., Renault, P., and Barquins, M., "Influence of implant length and bicortical anchorage on implant stress distribution," *Clinical Implant Dentistry and Related Research,* Vol. 5, No. 4, 2003, pp. 254-262.
9. Yokoyama, S., Wakabayashi, N., Shiota, M., and Ohyama, T., "The influence of implant location and length on stress distribution for three-unit implant-supported posterior cantilever fixed partial dentures," *Journal of Prosthetic Dentistry*, Vol. 91, No. 3, 2004, pp. 234-240.
10. Ivanoff, C. J., Grondahl, K., Sennerby, L., Bergstrom, C., and Lekholm, U., "Influence of variations in implant diameters: a 3- to 5-year retrospective clinical report," *International Journal of Oral and Maxillofacial Implants*, Vol. 14, No. 2, 1999, pp. 173-180.
11. Misch, C. E., "Implant design considerations for the posterior regions of the mouth," *Implant Dentistry*, Vol. 8, No. 4, 1999, pp. 376-386.

12. Tawil, G., Aboujaoude, N., and Younan, R., "Influence of prosthetic parameters on the survival and complication rates of short implants," *International Journal of Oral and Maxillofacial Implants*, Vol. 21, No. 2, 2006, pp. 275-282.

13. Zhang, L., Zhou, Y., and Meng, W., "A three-dimensional finite element analysis of the correlation between lengths and diameters of the implants of fixed bridges with proper stress distribution," *Hua Xi Kou Qiang Yi Xue Za Zhi*, Vol. 18, No. 4, 2000, pp. 229-231.

14. Huang, H. M., Tsai, C. M., Chang, C. C., Lin, C. T., and Lee, S. Y., "Evaluation of loading conditions on fatigue-failed implants by fracture surface analysis," *The International Journal of Oral & Maxillofacial Implants*, Vol. 20, No. 6, 2005, pp. 854-859.

15. Capodiferro, S., Favia., G., Scivetti, M., De Frenza, G., and Grassi, R., "Clinical management and microscopic characterisation of fatique-induced failure of a dental implant. Case report," *Head & Face Medicine,* Vol. 22, No. 2, 2006, pp. 18.

16. Winkler, S., Ring, K., Ring, J. D., and Boberick, K. G., "Implant screw mechanics and the settling effect: overview," *Journal of Oral Implantology*, Vol. 29, No. 5, 2006, pp. 242-245.

17. Naert, I., Quirynen, M., van Steenberghe, D., and Darius, P., "A study of 589 consecutive implants supporting complete fixture prostheses. Part II: prosthetic aspects," *Journal of Prosthetic Dentistry*, Vol. 68, 1992, pp. 949-956.

18. Tolman, D. E., and Laney, W. R., "Tissue integrated prosthesis complications," *International Journal of Oral & Maxillofacial Implants,* Vol. 7, 1992, pp. 477-484.

19. Hansson, S., and Werke, M., "The implant thread as a retention element in cortical bone: the effect of thread size and thread profile: a finite element study," *Journal of Biomechanics*, Vol. 36, No. 9, 2003, pp. 1247-1258.

20. Steigenga, J., Al-Shammari, K., Misch, C., Nociti, F. H. Jr., and Wang, H. L., "Effects of implant thread geometry on percentage of osseointegration and resistance to reverse torque in the tibia of rabbits," *Journal of Periodontalolgy*, Vol. 75, No. 9, 2004, pp. 1233-1241.

21. Nobel Biocare. Available online at: 'www.nobelbiocare.com'. Accessed December 2004.

22. 3i Implant Innovations, Inc. Available online at: 'www.3i-online.com'. Accessed November 2004.

23. Neoss Limited, *Neoss Implant System Surgical Guidelines,* Harrogate, United Kingdom, 2006.

24. Maeda, Y., Satoh, T., and Sogo, M., "In vitro differences of stress concentrations for internal and external hex implant–abutment connections: a short communication," *Journal of Oral Rehabilitation,* Vol. 33, 2006, pp. 75–78.

25. Merz, B. R., Hunenbart, S., and Belser, U. C., "Mechanics of the implant–abutment connection: an 8-degree taper compared to a butt joint connection," *International Journal of Oral and Maxillofacial Implants,* Vol. 15, 2000, pp. 519-526.

26. Khraisat, A., Stegaroiu, R., Nomura, S., and Miyakawa, O., "Fatigue resistance of two implant/abutment joint designs," *Journal of Prosthetic Dentistry,* Vol. 88, 2002, pp. 604–610.

27. Strand7 Pty Ltd, *Strand7 Theoretical Manual,* Sydney, Australia, 2004.

28. Guan, H., van Staden, R. C., Loo, Y. C., Johnson, N. W., Ivanovski, S., and Meredith, N., 2008, "Influence of bone and dental implant parameters on stress distribution in mandible – A finite element study," *The International Journal of Oral & Maxillofacial Implants*, (Accepted).

29. Lai, H., Zhang, F., Zhang, B., Yang, C., and Xue, M., "Influence of percentage of osseointegration on stress distribution around dental implants," *The Chinese Journal of Dental Research,* Vol. 1, No. 3, 1998, pp. 7-11.

30. van Staden, R. C., Guan, H., Loo, Y. C., Johnson, N. W., and Meredith, N. "Stress evaluation of dental implant wall thickness using numerical techniques," *Applied Osseointegration Research,* Vol. 6, No. 1, pp. 39-48.

31. Guan, H., van Staden, R. C., Loo, Y. C., Johnson, N. W., and Meredith, N., "Stress distribution in mandible influenced by Nobel Biocare, 3i and Neoss implant thread designs," *The Sixth International Conference on Engineering Computational Technology,* September 2-5, 2008 Athens, Greece (Accepted).

32. van Staden, R. C., Guan, H., Loo, Y. C., Johnson, N. W., and Meredith, N., "Comparative analysis of two abutment-crown connection systems - A finite element study," *Applied Osseointegration Research,* Vol. 6, No. 1, pp. 49-58.

33. van Staden, R. C., Guan, H., Johnson, N. W., Loo, Y. C., and Meredith, N. "Step-wise analysis of dental implant insertion process using finite element technique," *Clinical Oral Implants Research,* Vol. 19, No. 3, 2008, pp. 303-313.

34. Burstein, A. H., Reilly, D. T., and Martens, M., "Aging of bone tissue: mechanical properties", *The Journal of Bone and Joint Surgery. American Volume*, Vol. 58, No. 1, 1976, pp. 82-86.