# Quantification of Forces Dissipated Through Bone When Using Rapid Maxillary Expansion

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A thesis submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE (ORTHODONTICS)

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THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES

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# Quantification of Forces Dissipated Through Bone When Using Rapid Maxillary Expansion

BY

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Of

MASTER OF SCIENCE

## Abstract

**Quantification of Forces Dissipated Through Bone When Using Rapid Maxillary Expansion**

AIM: To Quantify the Forces Dissipated Through Bone When Using Rapid Maxillary Expansion

MATERIAL AND METHODS: Stress-strain gauges (Intertechnology, Don Mills, Ontario) were attached to human adult cadavers and bonded to the bone adjacent to the mid-palatal and intermaxillary sutures using the MBond 200, cyanoacrylate adhesive (Intertechnology, Don Mills, Ontario). The gauges were attached to a P3 machine and forces exerted on the craniofacial complex using a modified RME. Values generated were converted to force in gram units.

RESULTS AND DISCUSSION: After complete activation of the modified RPE appliance, maximum values were compiled and compared. The mean maximum force values for the mid-palatal suture was 986.58 grams (±203.72), while the intermaxillary suture site was 759.99 grams (±143.77). These forces are all at the level of orthopaedic in nature. Using a paired student t-test, it was found that there was a statistically significant difference in force values between the mid-palatal and intermaxillary sensor sites ($p<0.05$). No specimens were found to have either the mid-palatal or intermaxillary suture become patent following complete activation. The difference in values could indicate that the force generated by the modified RME becomes dissipated by the hard and soft tissues in the craniofacial complex and that the further away from the RME, the lower the recorded value. This may further support the theory that piezoelectricity mediates orthodontically induced alveolar remodelling by orthopaedic orthodontic appliances in the craniofacial complex.

CONCLUSIONS: Forces generated by RME devices are dissipated through the bone at levels that exceed orthopaedic force range. The further away from the site of force delivery, the lower the recorded values, suggesting dissipation involves many factors such as amounts of hard and soft tissue.

## Acknowledgements

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Last, and certainly not least, to my wife, Christina. It seems that words are inadequate to describe what you have meant to me since we met, and even more so over the last three years. Koukla, I would not be where I am today without your unselfish, untiring and unconditional love, devotion and support that you have provided me and our entire family. I am a very fortunate man to have such an extraordinary woman in my life: a best friend, a confidant, a teacher, the mother of my children. I love you with every bit of my heart and soul. You are an amazing and beautiful person. I look forward to our life together in a new setting, and all the exciting times ahead. Eugapae!

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## 1.0 INTRODUCTION AND STATEMENT OF THE PROBLEM

Rapid maxillary expanders (RMEs) are widely used orthopaedic appliances in orthodontics. The use of such expanders exerts forces on the teeth and bone that are dissipated throughout the craniofacial complex resulting in anatomical changes involving bone. Although the literature describes the areas to where this force is dissipated, there is lack of knowledge on the quantification of force at the applied areas and its dissipation throughout the craniofacial complex. Because these appliances are widely used, it is critical to have an understanding of these forces so that an optimal and efficient correction in a biological range can be obtained.

The goal of orthopaedics is to produce a more aesthetic and functional change in the shape of the craniofacial skeleton. This is undertaken by exerting controlled and directed mechanical forces in patients manifesting dentofacial deformities and craniofacial anomalies. This force exerts a strain on the sutures of the craniofacial complex resulting in microscopic changes that over time summate to result in macroscopic effects.

Sutural mechanical stresses during mastication are complex because of momentary changes in force direction, muscle function, complex sutural forms, and the irregular shape of craniofacial bones. Understanding this complex interplay of sutural growth could be the key to understanding the mechanism of action of orthopaedic loading. This will provide invaluable knowledge to the literature in the quest to determine the ideal mechanical stimuli that are necessary when using orthopaedic appliances. This ideal, is the minimum mechanical force that results in the maximum desirable skeletal modification in the shortest period of time. It is anticipated that information from this study will provide improved knowledge to assist clinicians using orthopaedics to provide this optimal force.

## 2.0 LITERATURE REVIEW

### *2.1 Embryology, Anatomy and Histology of the Palate and Sutures*

#### *2.1.1 Embryology*

The palate begins to develop early in week 6, but the process is not completed until the $12^{th}$ week. The most critical period during palatal development is the end of the $6^{th}$ week to the beginning of the $9^{th}$ week. The entire palate develops from two structures – the primary palate (premaxilla) and the secondary palate. The origin of the primary palate is the deep portion of the intermaxillary segment, which arises from the fusion of the two medial nasal prominences (Figure 1) (Persaud and Moore, 2002).

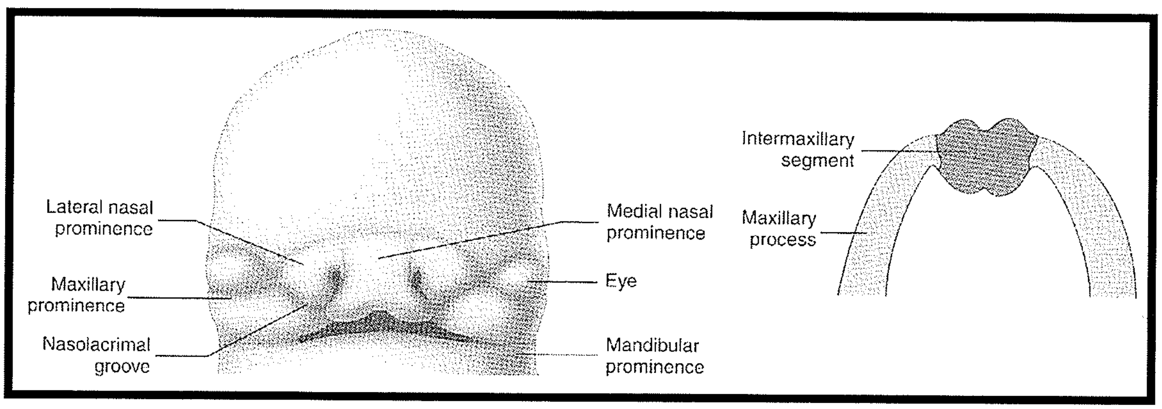



**Figure 1: Diagram depicting the formation of the palate from a frontal and coronal view.**

The secondary palate gives rise to the hard and soft palate posterior to the incisive foramen. It arises from paired lateral palatine shelves of the maxilla. These shelves are comprised initially of mesenchymal connective tissue and are oriented in a vertical plane with the tongue interposed. Later, the lateral palatine shelves become elongated and the tongue becomes relatively smaller and moves inferiorly. This allows the shelves to become horizontally oriented, to approach one another, and to fuse in the midline. The median palatal raphe is a clinical remnant of fusion between the palatine shelves, and the incisive foramen is present at the junction of the primary palate and the lateral palatine shelves. The lateral palatine shelves also fuse with the primary palate and the nasal septum. Fusion between the nasal septum and palatine processes proceeds in an AP direction beginning in the 9th week (Persaud and Moore, 2002)

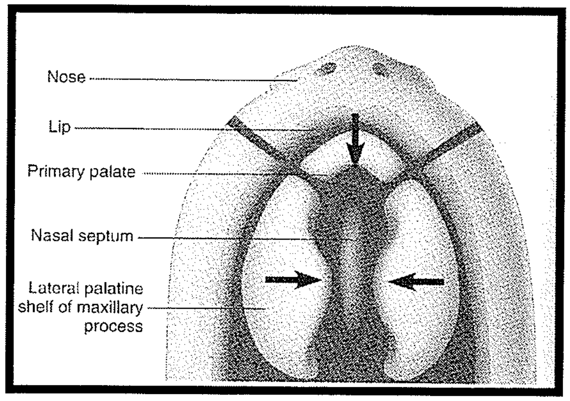



**Figure 2: Diagram depicting the formation and direction of the palate at 6 weeks.**

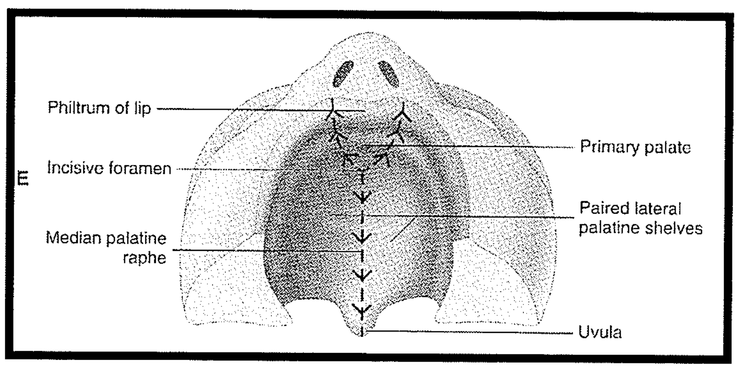


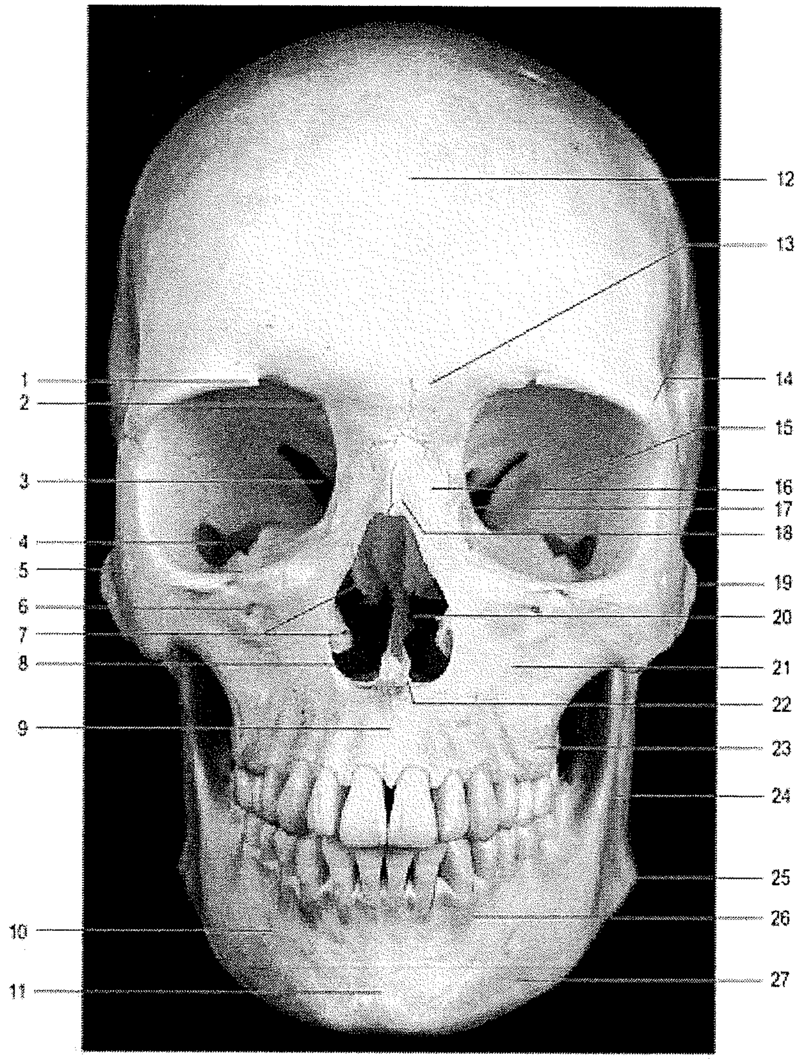

**Figure 3: Diagram depicting the formation and direction of the palate at 12 weeks.**

The interpremaxillary suture is well-established around the 47th day (Figure 2) of embryo development (primary palate). The first indication of sutural formation of secondary palate, in which the maxillary and palatine parts of the mid-palatal suture form, is at approximately 10½ weeks of age. A definite intermaxillary suture is established by the 12th week (Figure 3) (Persaud and Moore, 2002).

### *2.1.2 Anatomy*

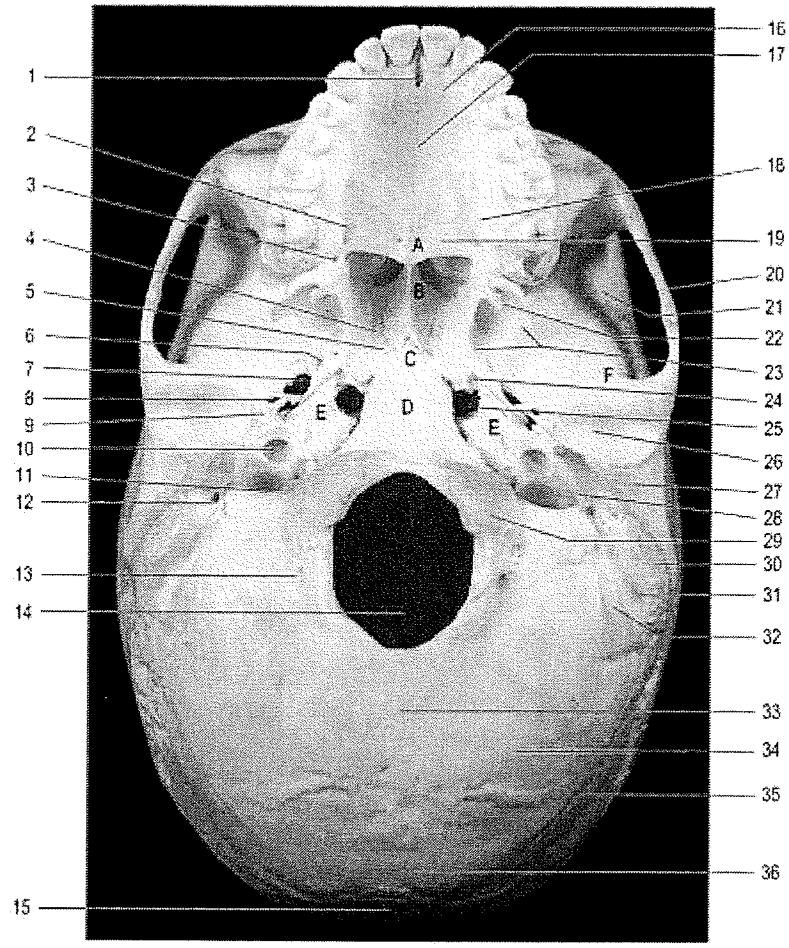
The maxilla is composed of 2 halves and can be conceptualized as a pyramidal body with 4 sides and 4 processes (Liebgott, 2001). Each maxilla articulates with the following structures (Liebgott, 2001) (Figures 4 and 5):

1. The opposite maxilla
2. The mandibular teeth (via the maxillary teeth and alveolar process)
3. Nasal bone
4. Lacrimal bone
5. Ethmoid bone
6. Palantine bone (via the palatal process)
7. Frontal bone (via the frontal process)
8. Vomer
9. Zygomatic bone (via the zygomatic process, which forms the apex of the pyramid)
10. Inferior concha



1. Supraorbital notch.
2. Frontal notch.
3. Superior orbital fissure.
4. Inferior orbital fissure.
5. Zygomaticofacial foramen.
6. Infraorbital foramen.
7. Nasal conchae.
8. Anterior nasal aperture.
9. Intermaxillary suture.
10. Mental foramen.
11. Mental protuberance.
12. Frontal bone.
13. Glabella.
14. Zygomatic process of frontal bone.
15. Greater wing of sphenoid bone.
16. Frontal process of maxilla.
17. Lacrimal bone.
18. Nasal bone.
19. Zygomatic bone.
20. Nasal septum.
21. Body of maxilla.
22. Anterior nasal spine.
23. Alveolus of maxilla (upper jaw).
24. Ramus of mandible.
25. Angle of mandible.
26. Alveolus of mandible (lower jaw).
27. Body of mandible.

**Figure 4: Front view of skull.**




1. Incisive fossa.
2. Greater palatine foramen.
3. Lesser palatine foramen.
4. Palatovaginal canal.
5. Vomerovaginal canal.
6. Sphenoidal foramen.
7. Foramen ovale.
8. Foramen spinosum.
9. Spine of sphenoid.
10. Carotid canal.
11. Jugular foramen.
12. Stylomastoid foramen.
13. Condylar canal.
14. Foramen magnum.
15. External occipital protuberance.
16. Palatine process of maxilla.
17. Median palatine suture.
18. Transverse palatine suture.
19. Horizontal plate of palatine bone.
20. Zygomatic arch.
21. Greater wing of sphenoid.
22. Pterygoid hamulus.
23. Medial and lateral pterygoid plates of sphenoid bone.
24. Opening of pterygoid canal.
25. Foramen lacerum.
26. Mandibular fossa.
27. External acoustic meatus.
28. Styloid process of temporal bone.
29. Occipital condyle.
30. Mastoid process of temporal bone.
31. Mastoid notch.
32. Groove for occipital artery.
33. External occipital crest.
34. Inferior nuchal line.
35. Superior nuchal line.
36. Squamous part of occipital bone.

A. Posterior nasal spine.
B. Vomer contributing to nasal septum.
C. Body of sphenoid.
D. Basilar part of occipital bone.
E. Petrous processes of temporal bones.
F. Articular eminence.

**Figure 5: Inferior view of skull.**

### *2.1.3 Histology*

It was found by Ten Cate and Freeman in 1977 that the immediate effect of applying tensile force to the palatal suture resulted in small localized tears within the suture, analogous to trauma. The tears then fill with tissue fluids, hemorrhage and an inflammatory cell infiltrate. Granulation tissue replaces the initial hematoma. A considerable number of fibroblasts and mesenchymal stem cells are recruited to the area, and synthesis of type I collagen occurs within the zone where the suture separates. As well, new capillaries form due to the vascular response present. During the active expansion phase, sutural expansion involves injury followed by repair. Regeneration does not occur until the cessation of sutural expansion. There is continued in-growth of new capillaries within this fibrous tissue, and osteoprogenitor cells recruited from the surrounding periosteum begin to deposit osteoid along the collagen fiber network. The response of the suture is one of osteogenesis and fibrillogenesis followed by remodeling (Ten Cate and Freeman, 1977)

Progressive remineralization of the soft callus is next, which is part of the stabilization phase. This phase results in the formation of a hard callus which is composed of immature bone or woven bone. This woven bone undergoes extensive remodelling to restore the normal lamellar architecture (Proffit and Fields, 2003). This returns the bone to its mature level within 3 months (Ekstrom and Henrickson, 1977).

### *2.2 History and Basis of RME*

Over 100 years ago, the foundation of dentofacial orthopaedics was established when Kingsley and Angle discovered that there was a favourable change in patients with dentofacial deformities and malocclusions when an exogenous mechanical stress was applied. The first published work reporting on this procedure appeared in 1860, when E.H. Angell described the rapid expansion of the upper arch to provide space for maxillary canines (Angell, 1860). Since then, a plethora of orthopaedic devices have been established, all having the goal of modifying or altering growth of the craniofacial complex (Proffit and Fields, 2000; Graber and Vanarsdall, 2005). These include headgears, functional appliances and RMEs. The evidence in the literature describing the clinical efficacy of these appliances is exhaustive. However, their exact mechanism of action remains unknown and is a major controversy in the orthodontic literature. It is thought that exogenous forces produced by these appliances result in sutural bone strain that causes a cellular response in growth (Mao, 2002). This bone strain can be measured on the cortical surface over the craniofacial sutures. Similarly, functional appliances result in an alteration of the muscles of mastication producing stress on the zygomatic, sphenoid and temporal bones due to the attachments of the masseter, temporalis and lateral pterygoid muscles which are articulated by various sutures. (Mao, 2002)

Hylander's macaque model and Herring's pig model have been the foundation of our current knowledge of *in vivo* skull loading in mastication. These *in vivo* bone strain experiments mathematically mapped out the strain endured by the craniofacial sutures in the macaque (Hylander, 1986) and pig (Herring 1991; Herring, Teng, Huang, Mucci and

Freeman, 1996) during mastication. They found that the mandibular condyle sustained large mechanical strain during mastication and the circum-orbital region endures little bone strain, despite the large amount of bone mass present (Picq and Hylander, 1989; Ross and Hylander 1996; Herring, 1991; Herring, Teng, Huang, Mucci and Freeman, 1996; Rafferty and Herring, 1999; Rafferty and Herrig, 2000; Ravosa, Vinyard and Hylander, 2000). Also, sutures withstand mechanical stresses without overstressing facial bones (Buckland-Wright, 1978). Work on goat skulls has demonstrated that sutures absorb considerable energy generated by impact mechanical forces suggesting the possibility that sutural cells and the extracellular matrix components may store strain energy (Jaslow, 1990; Jaslow and Biewener, 1995). Indeed, sutures are moveable joints and have been shown to undergo displacement with moderate orthopaedic forces (Kragt, Duterloo and Algra, 1986).

Sutures are complex soft connective tissue articulations only found in the craniofacial bones of the skull. They absorb and transmit forces from mastication or exogenous orthopaedic forces instantaneously. Sutures, along with epiphyseal plates, allow for longitudinal growth of the skull by bone apposition. Sutures are composed of fibrous connective tissue and epiphyseal plates are composed of hyaline cartilage. Sutural growth is induced by small doses of oscillatory strain as little as 600 cycles 10 minutes per day over 12 days. Oscillatory tensile and compressive strain induces anabolic sutural responses and turns on genes and transcription factors that activate cells through mechanotransduction pathways to stimulate growth. Growth therefore, occurs by hereditary and mechanical signals in the same genetic pathway (Mao, 2002).

The above evidence suggests that sutures experience and transmit mechanical stresses resulting in their modification. An extension from this thinking suggests that orthopaedic forces are also absorbed and transmitted by sutures. The minute movement of the sutural cells due to an orthopaedic force is a potential mechanism for them to activate a biological response.

The literature describes stress patterns of craniofacial bones with RME and headgear using dry skulls. It is assumed that the strain patterns in dry skulls are similar to those *in vivo*. Experiments assessing that sutural strain patterns upon *in vivo* headgear loading in *Macaca irus* are substantially similar to sutural strain patterns in the same locations of dry skulls of the same animals obtained after they are sacrificed (Buckland-Wright, 1978; Kannan, 1982). These experiments help validate the results of dry skull studies. Yet it is assumed that strain is less in dry skulls because they are more stiff than skulls *in vivo*.

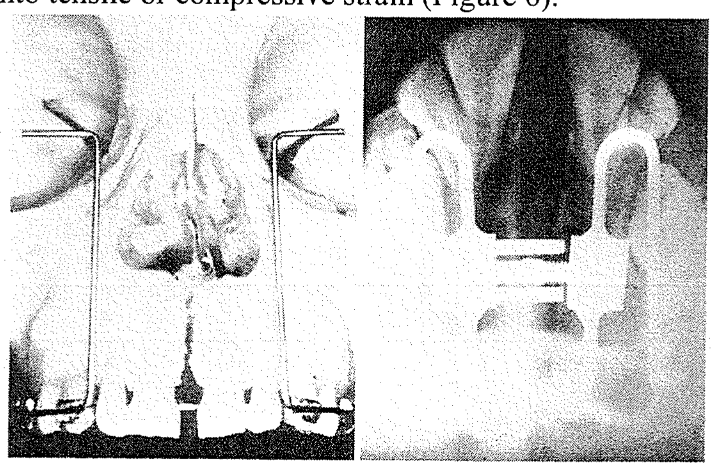
A dry skull experiment by Oberheim and Mao (2002) demonstrated that the average peak bone strain of the juvenile temporal articular eminence was significantly higher than the adult articular eminence. This was attributed to three factors:

1) a steeper articular eminence in adult skulls
2) increased distance from the mesiobuccal cusp of the maxillary first molar to the most inferior point on the articular eminence and
3) juvenile bone is more flexible than adult bone and is therefore subject to greater deformation and higher bone strain.

This suggests that similar orthopaedic forces (500 grams) could have different biological effects on immature and mature facial skeletons. They further found that contrasting bone strain patterns are present in the zygomatic arch across the zygomaticotemporal suture. There is an anatomical difference of the zygomatic arch as the middle is bent outwards and the ends are bent inwards. It was found that there was a tensile strain on its lateral surface, but compressive on its medial surface. This suggests potentially differential growth responses, bone remodelling and biomechanical effects of the zygomatic arch upon headgear therapy.

In summary, orthopaedic loading on the dentition results in a transmission of force to produce tensile and compressive strain on the facial and cranial sutures that absorb and transmit these forces. Different sutures experience different strain. Sutures absorb these stresses and their bony edges are displaced, either through tension or compression. This results in modulating sutural growth at the cellular level resulting in overall growth modification. Further, different sutures have different responses to force and propagate that force mainly into tensile or compressive strain (Figure 6).

A



B

**Figure 6: Opening of the mid-palatal suture on a dried skull (A). Radiographic appearance of the opened suture (B).**

### *2.3 Types of Appliances Used for Rapid Maxillary Expansion*

There is a wide array of appliances that can be utilized to accomplish rapid maxillary expansion:

1) ***Removable appliances***: These appliances provide mid-palatal splitting and are generally effective in the deciduous or early-mixed dentition. The predictability of these appliances is not great, and can be greatly enhanced by patient compliance and sufficient retention (Skieller 1964; Ivanovski 1985; Bishara and Staley, 1987).
2) ***Haas-type banded expander*** (tissue borne) (Haas 1965, 1980). This appliance is a fixed split acrylic appliance which consists of an expansion screw (spring-loaded or a jackscrew) with acrylic abutting the alveolar ridges. The expansion screw has been shown to deliver 3 to 10 pounds of orthopaedic forces (Issacson, Wood and Ingram, 1964). The appliance is normally attached to the teeth with bands on the first molars and first premolars.
3) ***Hyrax-type banded expander*** (Biederman, 1968). This tooth-borne appliance is a nonspring-loaded jackscrew with heavy wire extensions that are soldered to the palatal aspects of the bands on the first molars and premolars.
4) ***Minne-banded expander*** (Issacson, Wood and Ingram, 1964) is a heavy-caliber coil spring-loaded appliance adapted to bands placed on the first permanent molar.

5) ***Bonded expander***: This is basically a hybrid of the Haas-type appliance with acrylic covering the occlusal surfaces in a splint fashion. It must be chemically bonded to the maxillary teeth.

6) ***Fan-type rapid maxillary expander***: designed in 1996 by Schellino, (Levrini and Filippi, 1999). This expansion appliance incorporates a spider screw named "Ragno" which works asymmetrically and allows "fan opening" of the suture.

### *2.4 Rapid Maxillary Expansion in Adults*

RMEs are one of the most useful appliances used by orthodontists and has been part of the orthodontists armamentarium for over 100 years (Chaconas and Caputo, 1982)

RME's produce high forces that may directly or indirectly affect the ten bones associated with the craniofacial skeleton including the maxilla, mandible, nasal bone, temporomandibular joints and pterygoid plates of the sphenoid bone. Clinicians report difficulty with expansion after the pubertal growth period when the intermaxillary suture is thought to fuse (Bishara and Staley, 1987; Proffit, Fields and Sarver 2007; Işeri, Tekkaya, Oztan and Bilgiç, 1998; Haas, 1980; Hicks, 1978). On the other hand, there is evidence that expansion in young adults is possible (Handelman, Wang, BeGole and Haas, 2000; Stuart and Wiltshire, 2003).

Bone scintigraphy is a technique used to assess the metabolic activity of bone. It's commonly used to detect the vascularity or osteogenesis of bone activity. Baydas and coworkers (2006) performed scintigraphy studies on 17 females age 16.1 to 18.8 years.

Scintography was performed before expansion (T1), at the time the suture was split (T2) and then after the widening period (T3). Significant activity was observed between times T1 to T2 and then there was a remarkable decrease after the suture was opened from T2 to T3. This indicated that in these young female adults, rapid maxillary expansion resulted in not only dental but skeletal effects. This further suggests that RMEs should not be restricted to children. The question that remains to be answered is what is the upper age limit of expansion?

Because histological investigation is not feasible to assess the suture in our patients, an occlusal radiograph is a common technique used in clinical orthodontics to assess if the mid-palatal suture is ossified. A radiological-histological investigation by Wehrbein and Yildizhan analyzed the mid-palatal suture of ten subjects age 18 to 38 years who had recently died. It was found that 50% of the areas in which the suture was determined to be radiologically fused, no histological sutural obliteration was observed. The authors suggest that the term 'fusion' should be avoided when discussing radiological films of sutures. These findings suggest that radiographs should not be utilized to assist in the treatment decision if patients will be able to undergo maxillary expansion. The authors also found that the earliest signs of obliteration were observed in the posterior region of a 21 year old male and one 32 year old male demonstrated no obliteration at all.

In a study of human autopsy material, Melsen and Melsen (1982) described three stages of morphological development of the palatine suture without making reference to the age of the subjects. Their description is of a first stage involving a short, wide-shaped suture with the second stage more tortuous and the third stage an extensive heavy interlocking of the pterygomaxillary connection. They report that the third stage is resistant to vertical and horizontal displacement of the maxilla during rapid palatal expansion

Persson and Thilander (1977) performed a histological examination of autopsy material to investigate the intermaxillary and transverse palatine suture areas of the alveolar arch of twenty-four subjects age 15-35 years. They observed that the palatal sutures may show obliteration in juveniles but a marked degree of closure was rarely found until the third decade. Great variations existed among individuals with respect to the age that the suture began to close. The oldest subject with no signs of ossification was a 27 year-old woman and the earliest ossification was observed in a 15-year-old girl. Variations were also found in different parts of the same suture. Further the closure of the suture progresses more rapidly in the oral versus the nasal part of the palatal vault. The intermaxillary suture was found to close more often in the posterior area versus the anterior. They conclude that there are large inter-individual differences present and that there are other factors other than age that influence the start and advancement of suture closure. They suggest a limit of 5% obliteration of the suture for maxillary expansion to be performed and that most patients under the age of 25 years can undergo the procedure successfully.

Recently, Knaup and coworkers (2004) performed a histomorphometric analysis of autopsy material, from the anterior, median and posterior palate of 22 subjects age 18-63 years. Their goal was to determine the width and degree of obliteration of the mid-palatal suture between different ages. They found a statistically significant difference in the sutural width between the younger (<25 years) versus the older subjects. Similar to the results of Persson and Thilander, they discovered that the earliest ossifications tended to be observed in the posterior region, confirming a progression of ossification from posterior to anterior. The proportion of ossified tissue in the entire suture (obliteration) was low in all subjects, listed at 13.10%, which was found in a 44-year-old man in the older age group. The median value of the ossification was 0% in the younger age group and 3.11% in the group $\geq$ 26 years and this difference was found to be statistically significant. The earliest ossification was registered in a 21-year-old man and the oldest subject without ossification was a 54-year-old man.

A very interesting finding of this study was that ossification values were low in all subjects. No sutural region demonstrated more than 15% obliteration. Ossification values were not notably higher for elderly subjects. They suggest that this demonstrated that the bone bridges occurring sporadically within the suture are of no therapeutic significance during the first two decades and orthodontists should be fearful in performing rapid palatal expansion in patients beyond the third decade of life. They did not find bone remodelling or ossification activity lateral to the suture in subjects in the third or fourth decade. Based on Persson and Thilander's suggestion that maxillary expansion is possible with less than 5% obliteration, 77.3% of subjects over the age of 25 would qualify for expansion.

Clinically however, expansion is generally not considered in patients over 25 years due to other maxillary sutures and the age based rigidity of the maxillary bone that are thought to cause resistance to osseous transverse expansion (Isaacson and Ingram, 1964; Kokich, 1976; Melsen 1975; Wertz, 1970). Although the mid-palatal suture may break, there is resistance at the pterygomaxillary interface from the pterygoid plates of the sphenoid bones, which have a tendency to bend laterally and prevent the posterior area of the suture from opening (Wertz, 1970; Chaconas and Caputo, 1982; Jafari, Shetty and Kumar 2003).

In their finite element analysis study, Jafari, Shetty and Kumar (2003) indicates that the pterygoid plates are bent more than 2mm during rapid palatal expansion. Melsen and Melsen (1982) indicated that one cannot count on a spontaneous opening of the pterygomaxillary connection during a rapid palatal expansion due to its extensive interlocking. The stress from rapid maxillary expansion is transmitted to the cranial base only if a fixed pterygomaxillary connection is present and if spontaneous opening does not occur. Protecting the cranial base is therefore important as the elasticity of the bone structures decreases, especially the pterygoid plates of the sphenoid bone. During surgically assisted rapid palatal expansion, there should be a surgical severance of the pterygomaxillary connection (Matteini and Mommaerts, 2001; Holberg and Rudzki-Janson, 2006)

In a finite element analysis of the human cranial base by Holberg and Rudzki-Janson (2006), only moderate stresses were observed in the cranial base of children and adolescents during rapid palatal expansion suggesting that serious complications are unlikely. In the adult cranial base, due to its reduced elasticity, a considerable amount of stress was present when the pterygoid plates were slightly bent. This stress was particularly evident in the area of the foramen rotundum, the foramen ovale, foramen lacerum and the superior orbital fissure. This suggests that microfractures with injuries to the nervous and vascular structures may occur. Because of the reduced elasticity of the bony structures, considerable stress already occur on light bending of the pterygoid process, especially in the area of the foramen rotundum, the foramen ovale, the carotid sulcus, the optic foramen and the superior orbital fissure, all of which might lead to microfractures with injury of nervous and vascular structures. They suggest that clinicians should be mindful in monitoring the patients' bone elasticity during rapid palatal expansion and that protective measures should be placed in patients with decreased bone elasticity, such as decreasing activations or surgically severing the pterygomaxillary connection.

### *2.5 Craniofacial Forces from Rapid Maxillary Expansion*

The goal of rapid maxillary expansion is to produce a force to displace the palatal suture and expand the palate by forcing the halves laterally, with minimal tooth movement on tipping. This results in heavy forces directed to the maxilla and adjacent skeletal structures. Indeed, patients report pressure sensations at various craniofacial areas during RME, especially the areas articulating the maxilla such as the eyes and the nasal areas (Zimring and Isaacson, 1965; Chaconas and Caputo, 1982). Histological studies of animals where RME was employed also demonstrated signs of increased cellular activity at various craniofacial sutures. Histological studies have also demonstrated increased cellular activity at the nasal, maxillary-zygomatic and zygomaticotemporal sutures (Starnbach, Bayne, Cleall and Subtelny 1966). The nasal suture demonstrated the most activity. This has been confirmed by other histological studies (Gardner and Kronman, 1971; Starnbach and Cleall, 1964; Storey, 1973; Ten Cate, Freeman and Dickinson, 1977)

Isaacson and coworkers (1964) used strain gauges cemented to RMEs in patients and found that a single activation of the expansion screw of 0.2mm (one quarter revolution) produced approximately 1.3-4.5 kg (3-10 pounds) of force from a single activation. The measured forces were horizontal, vertical and a combination of the two. The force decayed rapidly initially and then continued to slowly decrease. Isaacson found that the resistance of the expansion was not from the mid-palatal suture but from the bones that articulated the maxilla because there was not a significant change in the force when the sutures opened. He found that a smaller force was required for younger patients versus older patients due to less resistance to expansion of the palate. Isaacson did not discuss the magnitude or the nature of changes which occur as activation continues.

Zimring and Isaacson (1965) did a similar study on four patients. They determined that it was the facial skeleton that was the main resistance to expansion. The maximum loads on patients ranged from 7.5-15.7 kg (16.6 to 34.8 pounds) of force during treatment and these forces gradually dissipated during the six week retention period. They reported forces in other areas such as the nose and beneath the eyes. They concluded that the magnitude and type of forces at these areas are not known.

Haas (1961) sacrificed pigs that had rapid maxillary expansion and found bending in the alveolus and lowering of the palatal vault. By using the data obtained from this pig study, he conducted expansion on human subjects. These subjects noted pressure in the alveolus, palatal vault and the articulations of the maxilla including the frontal, nasal and zygomaticomaxillary suture was recorded. Haas also reported some pressure at the zygomaticotemporal suture in his findings as well. Although these measurements were purely subjective in nature from the subjects, they aided in better understanding the dissipation of these forces.

Investigators have also conducted histological evaluations. Starnbach, Bayne, Cleall and Subtelny (1966) placed RME's on four rhesus monkeys and sacrificed each at different stages of treatment and retention. Histological analysis demonstrated disorganized periodontal fibres with a wider periodontal membrane on the palatal side. There was resorption of alveolar bone on the pressure surface. This was less evident in the animal that had been in retention. There was a predominance of lateral bodily movement over rotational movement. They were able to show greater cellular activity at the nasal, zygomaticomaxillary and zygomaticotemporal suture areas. The most activity was found at the nasal suture and least at the zygomaticotemporal suture.

Gardner and Kronman (1971) also did rapid palatal expansion in six rhesus monkeys and showed distortions at the lambdoid and parietal sutures and the sphenooccipital synchondrosis, by utilizing ultraviolet light. These sutures were split up to 1.5mm at some points, and on one skull the entire parietal bone was elevated above the calvarium. The spheno-occipital synchondrosis was also opened in all experimental subjects and in one animal, the rapid palatal suture expansion led to an opening of more than 1 mm. Histologically, growth or remodelling was evident in bones surrounding the mid-palatine suture such as the infratemporal region of the maxilla, greater wing of the sphenoid, zygomatic arch, pterygoid plates and hamular process.

Storey (1973) showed that the expansion is greater at the alveolar crest compared to the palatal vault. His study involved placing helical torsion springs on the upper lateral incisors of rabbits. Also, the maxillary bones swing laterally with a centre of rotation near the frontonasal suture.

In a study at the University of Manitoba, Murray and Cleall (1971), it was shown that the actual opening of the suture occurred during the fourth to seventh day of expansion in monkeys. It was observed that opening the suture involved a series of distinct stages. There was first an adaptation of the sutural connective tissue to heavy forces, then a proliferation of connective tissue and heavy resorption. This allowed a physical separation of the bony processes. There was then a heavy deposition of bone to maintain the expansion. Furthermore, they found that during the initial stages of expansion, tipping was observed in the buccal dentition, but after 14 days, bodily movement was occurring.

A clinical study by Wertz and Dreskin (1977) on 56 patients aged 8 to 29 years and having undergone expansion therapy with a variety of fixed expansion screw appliances, showed that opening of the palatal suture resulted in the displacement of the maxilla downward and usually forward. This confirmed the work by Gardner and Kronman (1971) who contended that the opening of the spheno-occipital synchondrosis was the reason for the anterior movement of the maxilla. They also showed that older patients had lost the width and younger patients did not have relapse. The older patients had more rigid skeletal components and had little orthopaedic change.

In a study in which metallic markers were placed bilaterally in the maxilla of five patients with bilateral posterior crossbite, age 10-15 years, Hicks (1978) found that a continuous 0.9 kg (2 pound) load was able to separate the two maxillary segments over a 1-3 week time period.

In a study of 32 patients who underwent rapid maxillary expansion, Timms (1980) demonstrated that the palatine bones separated as well as the maxilla and that the pterygoid processes of the sphenoid bone splayed outward. He noted that in subjects undergoing rapid maxillary expansion, the effect is greatest in the dentoalveolar region while it lessens as you move away and as the stress eases.

In a photoelastic study of the human skull, Chocanos and Caputo (1982) measured stresses using RME of the Haas, Minne-expander, Hyrax, and quad helix types. Each of the appliances produced different stresses transmitted through the bones of the craniofacial complex and effects on the various sutures. This was a result of their having a different range of load-activation characteristics. Fixed appliances produced stress that was concentrated in the anterior region of the palate that progressed posteriorly toward the palatine bone. The Haas, Minne-expander, and Hyrax appliances resulted in stresses that were in the orthopedic range. The stress was concentrated in the anterior region of the palate and progressed to the posterior and radiated to areas superiorly along the perpendicular plates of the palatine bone deeper to anatomic structures such as the lacrimal, nasal, and malar bones, the pterygoid plates of the sphenoid, the zygomatic process and the medial wall of the orbit. Interestingly, increased activation decreased retention resulting in less of a stress produced at these areas. Furthermore, with increased activation, the palate began to separate. The appliance was found to primarily affect posterior teeth. The quad helix appliance was found to produce less than the orthopaedic range of force and was a less effective appliance unless it was used in the very young patient in whom the sutures are patent.

Jafari, Shetty and Kumar (2003) analyzed stress distribution using 3-D finite element analysis on a young dry skull that received rapid maxillary expansion. He found that maximum lateral displacement was 5.313mm at the region of upper central incisors and there was a marked lateral displacement at the inferior aspect of the pterygoid plates. The pterygoid plates approximating the cranial base were minimally displaced. Midline structures experienced a downward displacement with ANS and A point moving down. The expansive forces were found to be distributed throughout the craniofacial skeleton.

## 3.0 OBJECTIVES AND NULL HYPOTHESIS

**<u>Objective #1:</u>** To quantify the force levels generated at the mid-palatal suture during activation of the RME appliance.

***Null Hypothesis #1:*** There are no measurable force levels detectable at the mid-palatal suture after activation of the RME.

***Null Hypothesis #2:*** The force levels generated at the mid-palatal suture are not orthopaedic in nature (500 grams/16 oz or higher).

***Null Hypothesis #3:*** The maximum force levels generated at the mid-palatal suture do not exhibit statistically significant differences between cadavers.

**<u>Objective #2:</u>** To quantify the force levels generated at the intermaxillary suture during activation of the RME appliance.

***Null Hypothesis #4:*** There are no measurable force levels detectable at the intermaxillary suture after activation of the RME.

***Null Hypothesis #5:*** The force levels generated at the intermaxillary suture are not orthopaedic in nature (500 grams/16 oz or higher).

***Null Hypothesis #6:*** The maximum force levels generated at the intermaxillary suture do not exhibit statistically significant differences between cadavers.

**Objective #3:** To determine if the mid-palatal suture remains fused or separates following activation of the RME appliance.

***Null Hypothesis** #7:* The mid-palatal suture will not break following activation of the RME appliance due to the advanced age of the specimens.

## 4.0 METHODOLOGY

### *4.1 Fabrication of a Universal RME Appliance*

A stock alginate tray (Ortho Organizers, U.S.A.) that was both perforated and possessed a rim-lock edge was used in an effort to increase the retentive capabilities of the tray. The tray was then modified by cutting it into 2 equal halves and joined in the center by a jack-screw (Forestadent, Pforzheim, Germany) soldered to each half in an anterior and posterior contact point. This jack-screw was capable of expanding a maximum of 12mm in total (Figure 7).

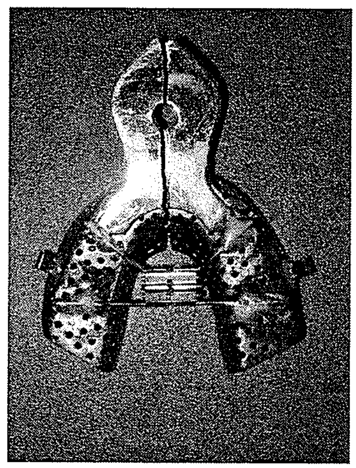


**Figure 7: 12mm hyrax expansion screw soldered to a sectioned impression tray**

### *4.2 Sample Selection*

Permission was obtained by Dr. Thomas Klonisch of the Faculty of Medicine to perform this study. Human cadavers were selected from those available in the Gross Anatomy Laboratory at the University of Manitoba, Faculty of Medicine. Ethics approval was not necessary as these cadavers were already given the designation for research purposes.

Cadavers were chosen that had at least molars and premolars present to allow for better, natural retention of the fabricated RME appliance. The following cadavers were chosen for the study:

| | |
|---|---|
| Specimen #24009 | Male 74 years old. |
| Specimen #24021 | Female 79 years old. |
| Specimen #23002 | Male 68 years old. |
| Specimen #23011 | Female 71 years old. |

### *4.3 Dissection for Sensor Placement*

Careful dissection of the cadaver was performed in the palatal and intermaxillary area. In the palatal area, a surgical scalpel was used to place an incision through the keratinized gingival tissue of the palate. This incision followed the line of the teeth (if present) and/or the residual alveolar ridge from the posterior aspect of the second molar to the midline. Next a flap was raised using a periosteal elevator (Hu-Freidy, Chicago, Illinois) to expose bone. The gingival tissue was then removed and discarded in accordance to the rules and regulations governing cadavers at the University of Manitoba. The complete bony palate was now exposed and ready to receive a rosette strain gauge sensor.

For the intermaxillary area, a surgical scalpel was used to cut the gingival tissue in the maxillary anterior area. This incision followed the line of the maxillary anterior teeth (if present) and/or the residual alveolar ridge from the area of the first premolar to the midline. Next a flap was raised using a periosteal elevator to expose the bone. This flap of tissue was then kept away from the rosette strain gauge site using a retraction fork. Half of the maxillary bone was now exposed and ready to receive a rosette strain gauge sensor.

### *4.4 Sensor Placement*

Once the bone was exposed in either the palatal or intermaxillary sites, it was then cleaned thoroughly with guaze dipped in a 99.9% pure ethanol solution for 5 minutes. Next, dry guaze was used to remove any and all moisture from the respective areas for another 5 minutes. A rosette strain gauge sensor equipped with 6, 10 foot leads (catalogue number C2A-06-062LR-350 (Intertechnologies), Figure 8) was then cemented to the dried bone using MBond200 (Intertechnologies), a cyanoacrylate bonding adhesive (Figure 9). Firstly, MBond 200 catalyst (98% 2-Propanol, 2% n-Phenyldiethanolamine) was brushed onto the back of the sensor and allowed to dry for 10 seconds. Secondly, the MBond 200 cyanoacrylate adhesive was placed on the back of the sensor. With firm finger pressure, the sensor was placed in position and held for 1 minute to allow the adhesive to dry and ultimately bond to the bone.

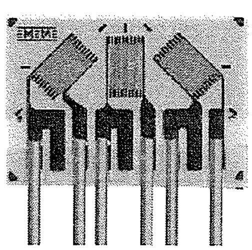


**Figure 8: A rosette strain gauge sensor equipped with 6, 10 foot leads (catalogue number C2A-06-062LR-350 (Intertechnologies))**

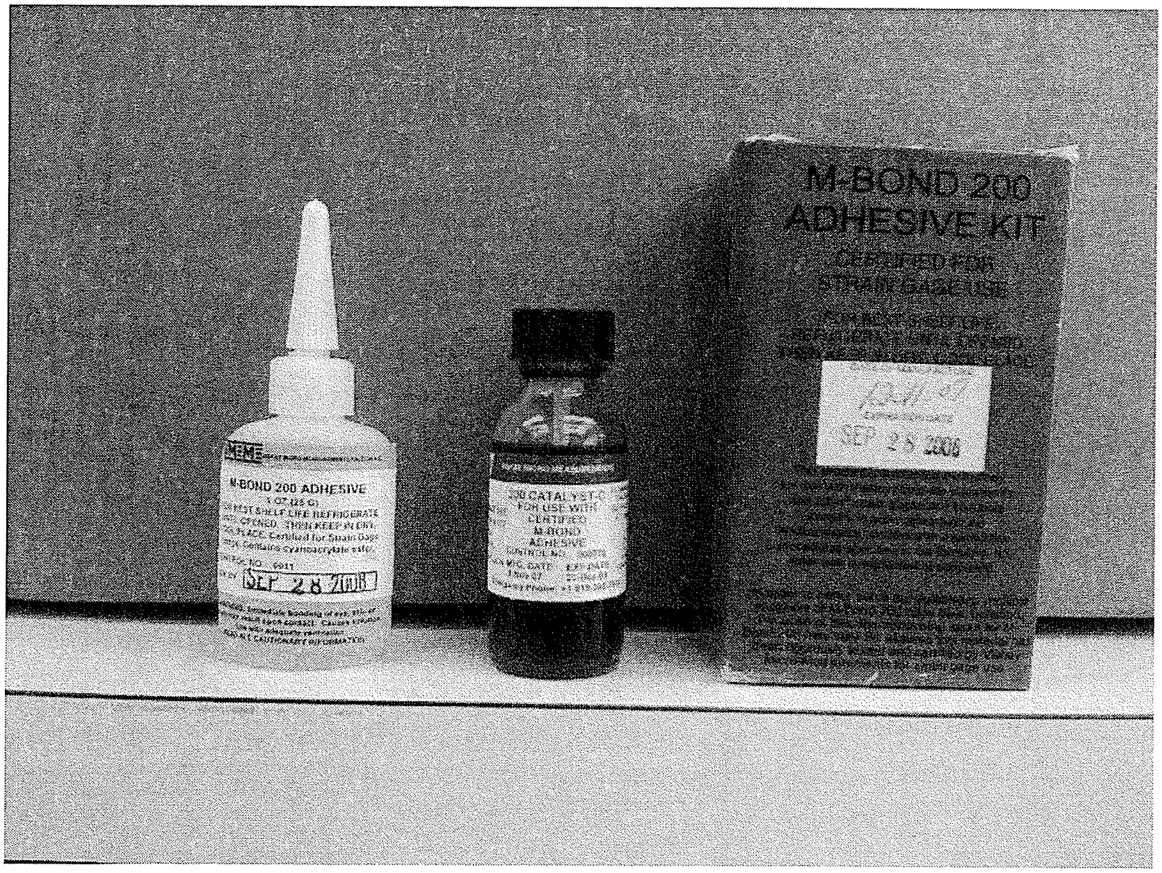



**Figure 9: M-Bond 200 (Intertechnologies)**

For the palatal suture, the sensor was placed 2mm to the right of the mid-palatal suture and midway between the anterior segment and the junction of the palatal process of the maxillary bone/palatine bone. The orientation of the sensor was such that the leads faced posteriorly or towards the cadaver's throat. For the intermaxillary suture, the sensor was placed 2mm to the right of the intermaxillary suture and 5mm gingival to the highest point of bone from the tooth or residual alveolar ridge. The orientation of the sensor was such that the leads faced inferiorly or towards the cadaver's throat. All leads were then connected to the P3 measuring device (Intertechnology, Toronto, Ontario, Figure 10) such that the first 2 leads were connected to Channel 1, the middle 2 leads were connected to Channel 2, and the last 2 leads were connected to Channel 3.

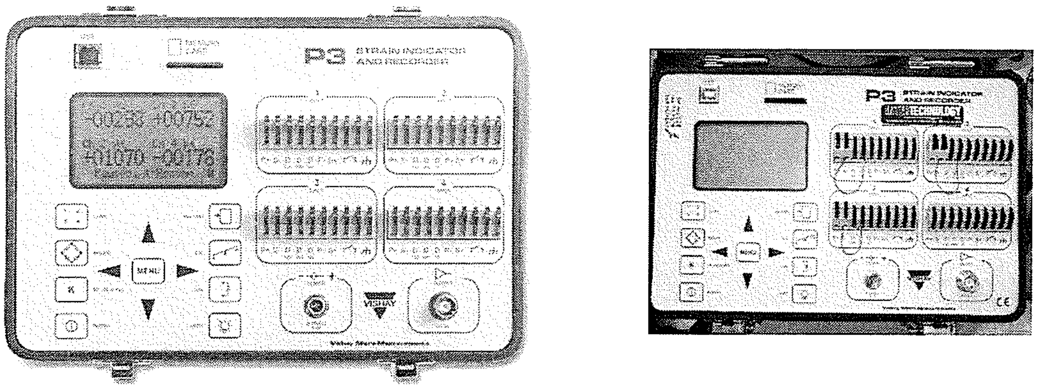



**Figure 10: P3 Strain gauge recording device (Intertechnologies)**

Once attached to the P3, an ohm meter (Canadian Tire, Toronto, Ontario, Figure 11) was used to ensure that all channels were grounded and stable. If any channels produced readings that were different from the others, this meant that the sensor was not stable and needed to be removed. A stable reading was one where the indicator bar remained stationary in the same range for all channels 1 through 3.

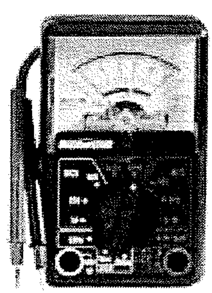


**Figure 11: Ohm Meter (Canadian Tire)**

Once confirmation of proper placement and functionality (through the ohm meter test) of the sensor was confirmed, the RME appliance was placed.

### *4.5 Placement and Activation of the RME Appliance and Recording of Strain Values*

Kerr brown dental compound (GAC Dentsply, USA) was placed in a water bath and heated to 60 °C. Once this temperature was reached, the compound material was placed and moulded into the modified RME device. The RME was immediately and carefully placed into the oral cavity of the cadaver, seated fully and held into place for 10 minutes to allow for the compound material to cool and harden. Once cooled, the P3 recording device was activated to record changes in the sensor at every second. The RME device was continually activated or turned every 5-10 seconds with use of a special key until it could not be turned any further, for a total of 48 turns or 12 mm. Once the final turn was completed, the P3 was kept in the record mode for another 60 seconds. Results were stored directly on the P3 device on a SD memory card and accessed via personal computer into a Microsoft Excel file (Microsoft Corp., Redmond WA) for analysis.

### *4.6 Organization of Data and Statistical Analysis*

All measurements obtained from the P3 were placed in table form corresponding to the respective channels, namely 1, 2, and 3. Data was then put through a complex mathematical macro developed by Intertechnology Canada to convert the μstrain value and incorporate the multi-directional axes of the rosette strain gauge into a useable format, namely force in grams. Data was analyzed using SPSS Version 15.0 statistical software (2007 SPSS Institute Inc., Chicago, IL). A two-tailed, paired Student t-test was used to compare the maximum and minimum force values at the different sites for statistical significance between sites and cadavers. A paired t-test is used when each data point in one group corresponds to a matching data point in the other group. The paired t-test is used to investigate the relationship between two groups where there is a meaningful one-to-one correspondence between the data points in one group and those in the other, e.g. a variable measured at the same time points under experimental and control conditions. Two-tailed tests are used where there is no basis to assume that there may be a significant difference between the groups (Hassard, 1991).

## 5.0 RESULTS

### *5.1 Cadaver 1 Results*

Cadaver 1 yielded the results shown in Figure 12. At first glance it can be observed that there are generally 4 distinct patterns present for each site. For the palatal sensor site, the first phase can be seen as a gradual increase in force values between 0 and 200 seconds. Between 200 and 600 seconds, there is a logarithmic increase in force values with a corresponding levelling-off between 600 and 815 seconds. The final phase shows a slight decline from the initial levelling-off between 815 seconds and the final reading of about 1050 seconds. The intermaxillary sensor site also showed a similar trend, however at different time intervals when compared to the palatal suture site. The first phase is comparable and occurs between 0 and 200 seconds. The second phase, or the logarithmic increase in force values occurred for a shorter overall period between 200 and 450 seconds. The third phase, or the levelling-off portion of the graph occurred between 450 and 750 seconds. The final or fourth phase was observed between 750 and the final reading of about 1050 seconds. The display of a spike in the graph occurred at each activation followed by a period of gradual relaxation and corresponding drop in the force value over time. These spikes were as high as 150 grams of force. The mid-palatal sensor yielded higher force values versus the intermaxillary sensor. According to Table 1, one can view the maximum and minimum values for both sensor sites.

| | Mid-palatal | Intermaxillary | Difference |
|---|---|---|---|
| **Minimum** | 319.18 | 111.58 | 207.60 |
| **Maximum** | 980.27 | 862.89 | 165.38 |

**Table 1: Maximum and minimum force values (grams) for cadaver 1**

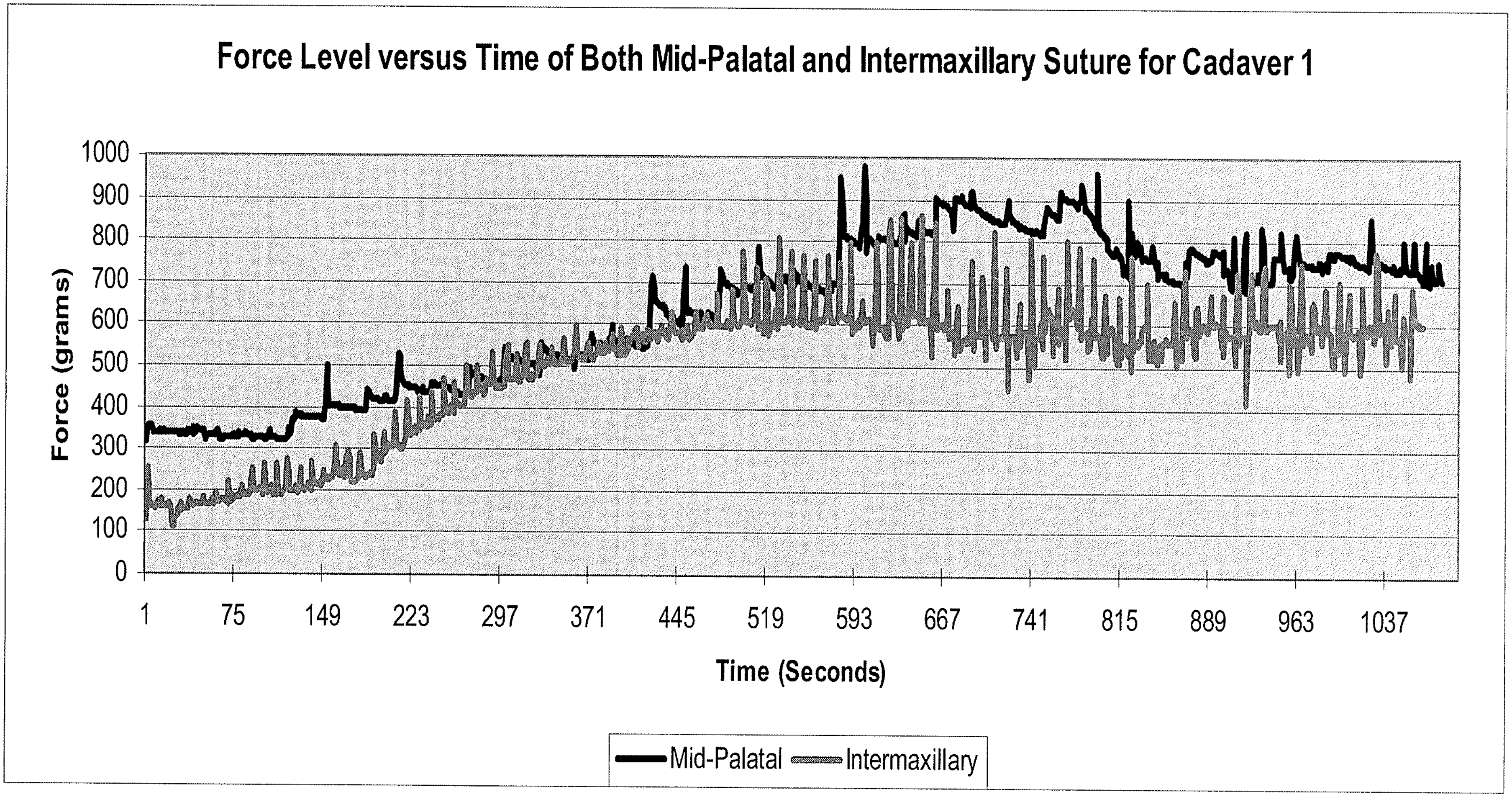



**Figure 12: Force level (grams) versus time (seconds) of both mid-palatal and intermaxillary suture for cadaver 1**

### *5.2 Cadaver 2 Results*

Cadaver 2 yielded the results shown in Figure 13. This cadaver displayed results that were similar to Cadaver 1. Again, 4 distinct patterns were present for each site. For the palatal sensor site, the first phase can be seen as a gradual increase in force values between 0 and 50 seconds. Between 50 and 175 seconds, there is a logarithmic increase in force values with a corresponding levelling-off between 175 and 275 seconds. The final phase shows a slight decline from the initial levelling-off between 275 seconds and the final reading of about 500 seconds. The intermaxillary sensor site also showed a similar trend, again at different time intervals when compared to the palatal suture site. The first phase occurs between 0 and 50 seconds. The second phase, or the logarithmic increase in force values occurred for a shorter overall period between 50 and 150 seconds. The third phase, or the levelling-off portion of the graph occurred between 150 and 350 seconds. The final or fourth phase was observed between 350 and the final reading of about 500 seconds. Between 300 and 350 seconds, the plateau reached similar levels but here the intermaxillary suture produced higher spikes. The same spikes in the level of force generated were observed at each activation followed by a period of gradual relaxation and corresponding drop in the force value over time. What is notably different in this cadaver is the level of spikes observed with each RME activation. Some spikes yielded increases of almost 300 grams. The mid-palatal sensor yielded higher force values versus the intermaxillary sensor. Table 2 describes the maximum and minimum values for the both sensor sites.

| | Mid-Palatal | Intermaxillary | Difference |
|---|---|---|---|
| **Minimum** | 461.36 | 357.22 | 104.14 |
| **Maximum** | 1152.42 | 835.84 | 316.58 |

**Table 2: Maximum and minimum force values (grams) for cadaver 2**

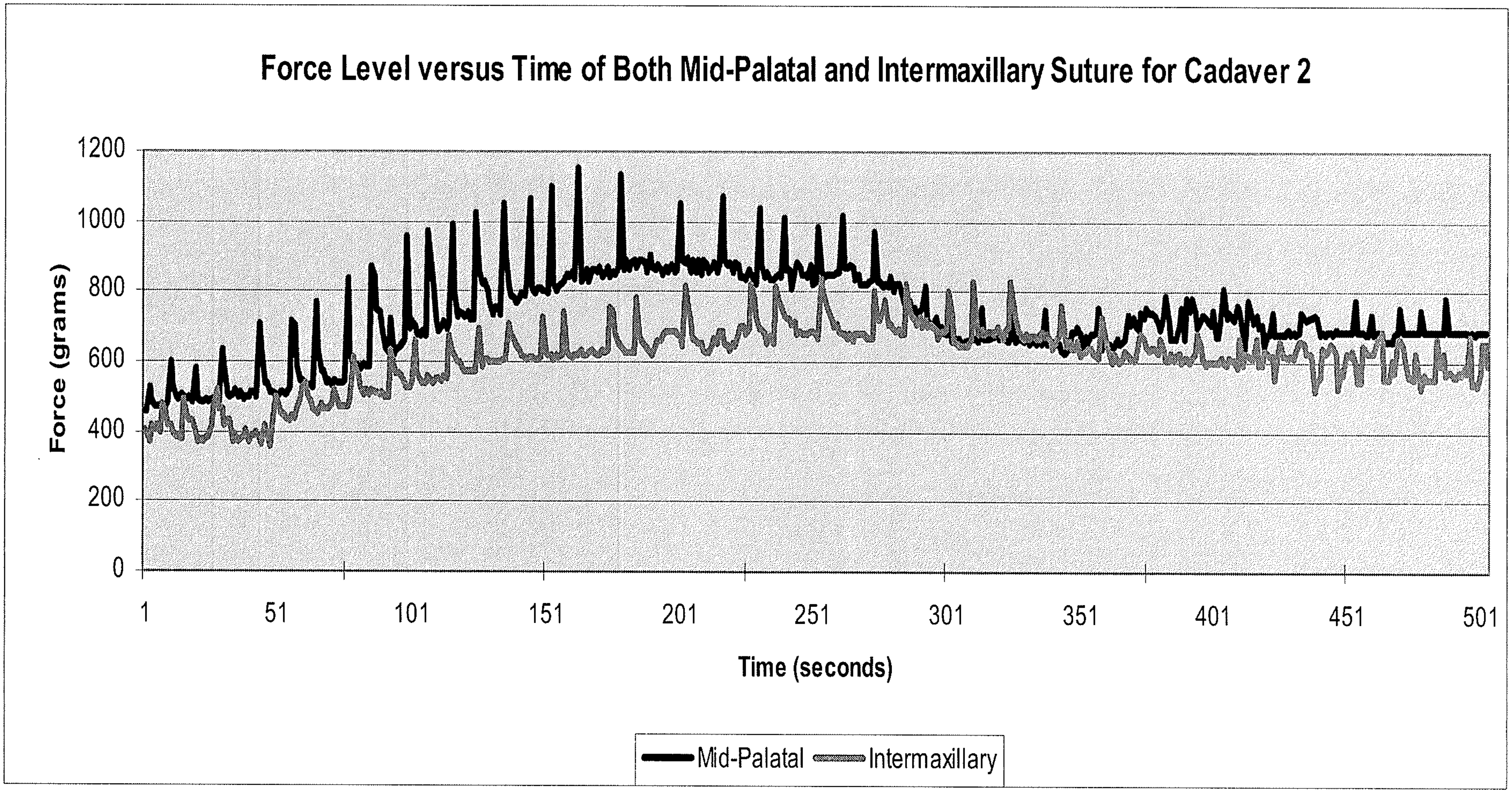



**Figure 13: Force level (grams) versus time (seconds) of both mid-palatal and intermaxillary suture for cadaver 2**

### *5.3 Cadaver 3 Results*

Cadaver 3 yielded the results shown in Figure 14. This cadaver again displayed results that were similar to the previous cadavers. Again, 4 distinct patterns were present for each site, however a different pattern emerged for the intermaxillary sensor site. For the palatal sensor site, the first phase can be seen as a gradual increase in force values between 0 and 70 seconds. Between 70 and 200 seconds, there is a logarithmic increase in force values with a corresponding levelling-off between 200 and 300 seconds. The final phase shows a slight decline from the initial levelling-off between 300 seconds and the final reading of about 550 seconds. The intermaxillary sensor site also showed a similar trend, again at different time intervals when compared to the palatal suture site. The first phase occurs between 0 and 140 seconds. The second phase, or the logarithmic increase in force values occurred over a longer overall period between 140 and 300 seconds. The third phase, or the levelling-off portion of the graph occurred between 300 and 450 seconds. A sudden drop can then be seen at approximately 451 seconds, followed by the final or fourth phase was observed between 451 and the final reading of about 550 seconds. The same spikes in the level of force generated were observed at each activation followed by a period of gradual relaxation and corresponding drop in the force value over time. The level of increase in these spikes ranged from approximately 200 grams for the mid-palatal sensor site and 50 grams for the intermaxillary sensor site. The mid-palatal sensor yielded higher force values versus the intermaxillary sensor. At about 320 seconds, similar force levels were attained at both sites. According to Table 3, one can view the maximum and minimum values for the both sensor sites.

| | Mid-Palatal | Intermaxillary | Difference |
|---|---|---|---|
| **Minimum** | 361.46 | 199.55 | 161.91 |
| **Maximum** | 1112.05 | 792.49 | 319.56 |

**Table 3: Maximum and minimum force values (grams) for cadaver 3**

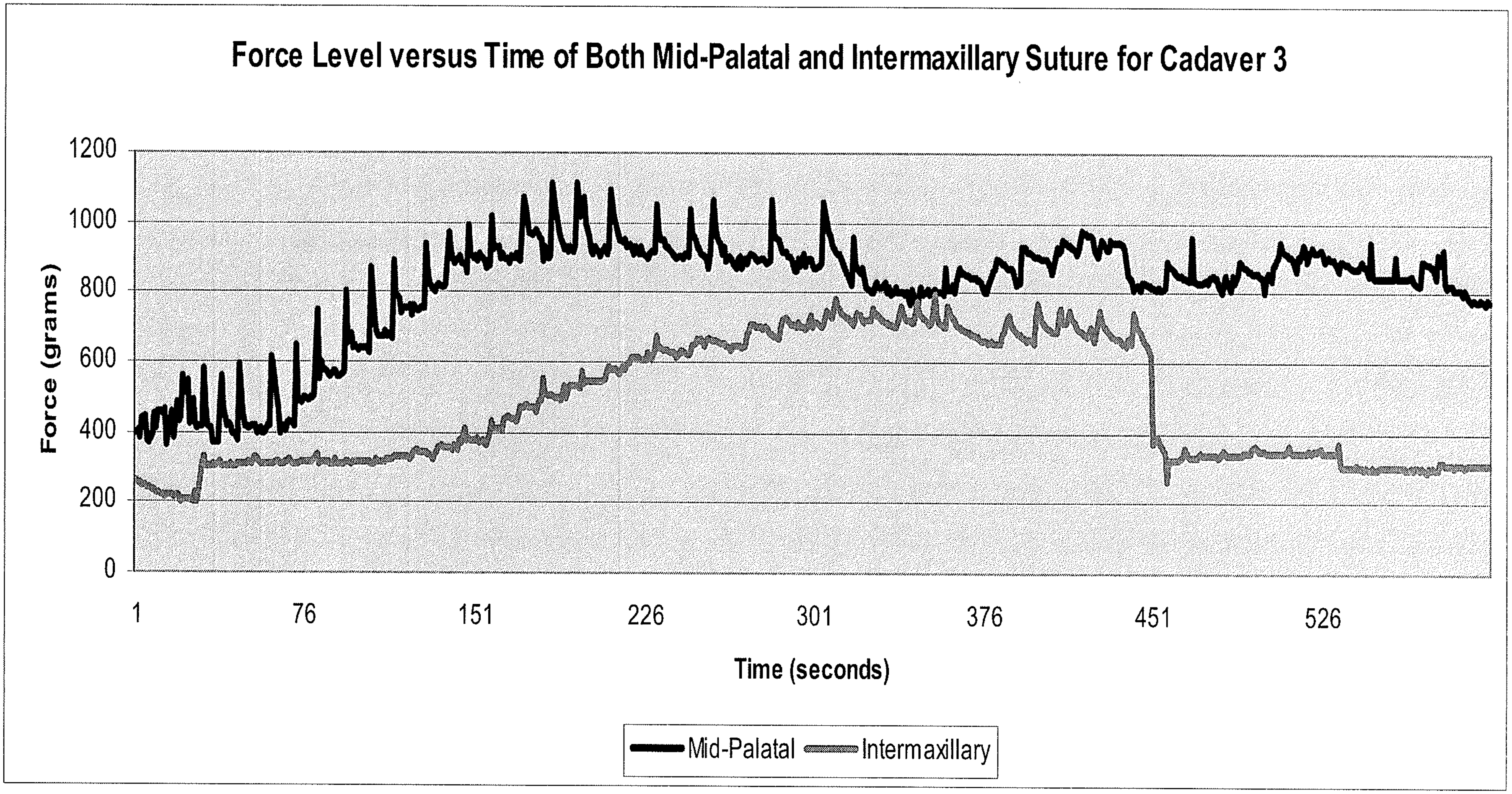



**Figure 14: Force level (grams) versus time (seconds) of both mid-palatal and intermaxillary suture for cadaver 3**

### *5.4 Cadaver 4 Results*

Cadaver 4 yielded the results shown in Figure 15. This cadaver again displayed a distinct pattern different from the other cadavers, but with generally the same phases. For the palatal sensor site, the first and second phase appear to blend into one between 0 and 135 seconds. Instead of a steady or logarithmic increase in force values, there are spikes and dips not seen before with the other cadavers. Then between 135 and 250 seconds, there is a levelling-off of force values. The final phase shows a slight decline from the initial levelling-off between 250 seconds and the final reading of about 350 seconds. The intermaxillary sensor site displayed the generic pattern we have seen in the other cadavers with the first phase occurring between 0 and 100 seconds. The second phase, or the logarithmic increase in force values occurred over a short period between 100 and 125 seconds. The third phase, or the levelling-off portion of the graph occurred between 125 and 250 seconds, however in this portion, there were not as many spikes present as was customarily seen on the other cadavers. The final or fourth phase was observed between 251 and the final reading of about 300 seconds. The same spikes in the level of force generated were observed at each activation followed by a period of gradual relaxation and corresponding drop in the force value over time. The level of increase in these spikes ranged from approximately 100 grams for the mid-palatal sensor site and 50 grams for the intermaxillary sensor site. The mid-palatal sensor yielded higher force values versus the intermaxillary sensor. At ±50 seconds, ±110 and ±251 seconds, similar force levels were displayed by both sites. According to Table 4, one can view the maximum and minimum values for the both sensor sites.

| | Mid-Palatal | Intermaxillary | Difference |
|---|---|---|---|
| **Minimum** | 319.44 | 312.63 | 6.81 |
| **Maximum** | 701.59 | 548.77 | 152.82 |

**Table 4: Maximum and minimum force values (grams) for cadaver 4**

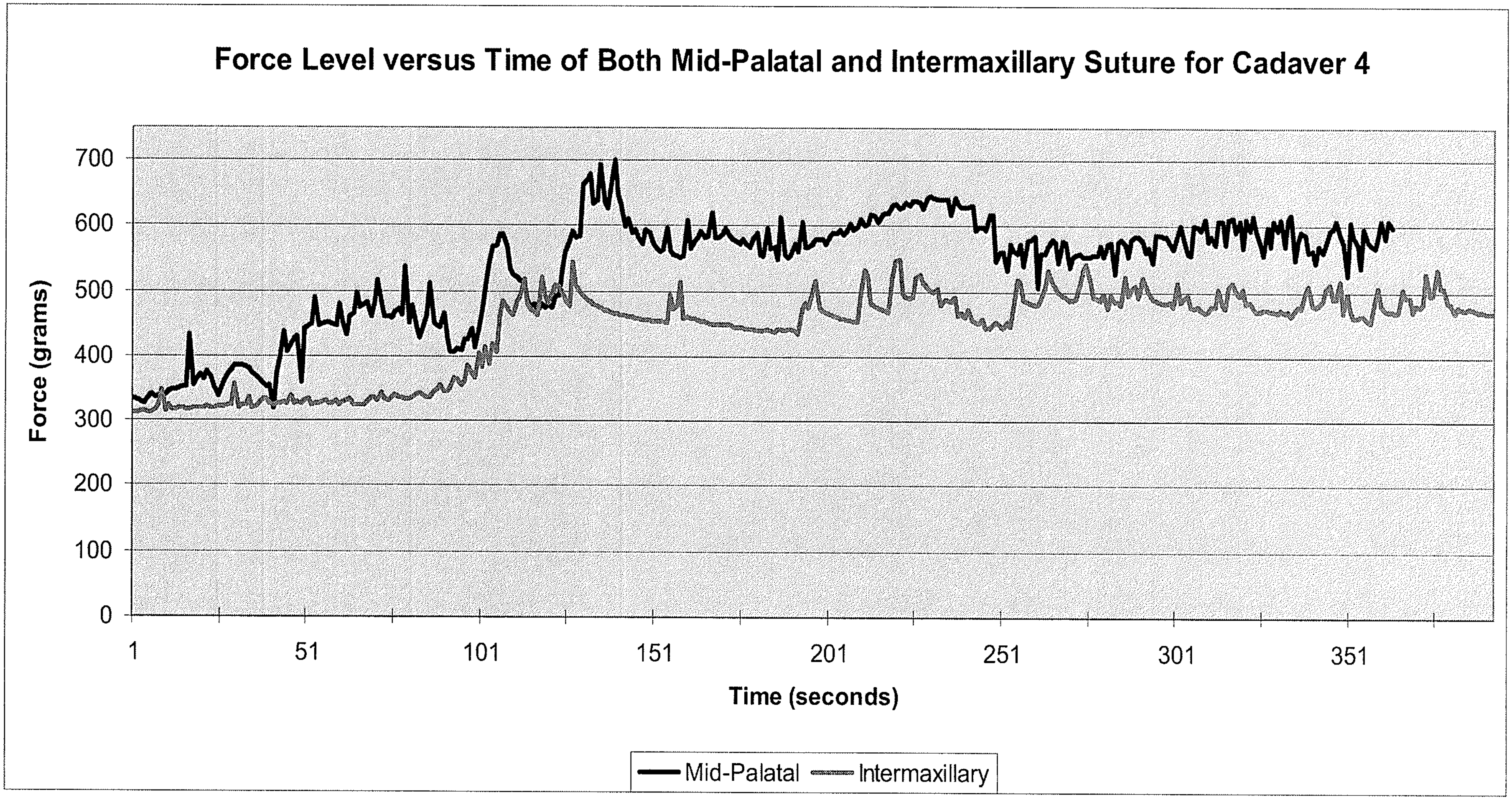



**Figure 15: Force level (grams) versus time (seconds) of both mid-palatal and intermaxillary suture for cadaver 4**

### *5.5 Mid-Palatal Suture Comparisons*

A comparison of the mid-palatal sensor site results of all cadavers tested (1 through 4) is displayed by Figure 16. It is apparent that Cadaver 4 produced the lowest force values while Cadaver 2, the highest. This is also described in Table 5. Another interesting observation is that Cadavers 2, 3 and 4 appear to follow the same logarithmic trend in increasing force levels in the 2 phase of RME activation. Although Cadaver 1 also shows an increase, it is more gradual as compared to the others. Finally it is apparent that Cadaver 1 was the longest test to perform, while Cadaver 4 was the shortest.

Using the unpaired t-test, we find that there is no statistical significance between cadavers for the maximum and minimum force values obtained.

| | Maximum | Minimum | Difference |
|---|---|---|---|
| **Cadaver 1** | 980.27 | 319.18 | 661.09 |
| **Cadaver 2** | 1152.42 | 461.36 | 691.06 |
| **Cadaver 3** | 1112.05 | 361.46 | 750.59 |
| **Cadaver 4** | 701.59 | 319.44 | 382.15 |

**Table 5: Maximum and minimum force values (grams) of the mid-palatal sensor site for all cadavers**

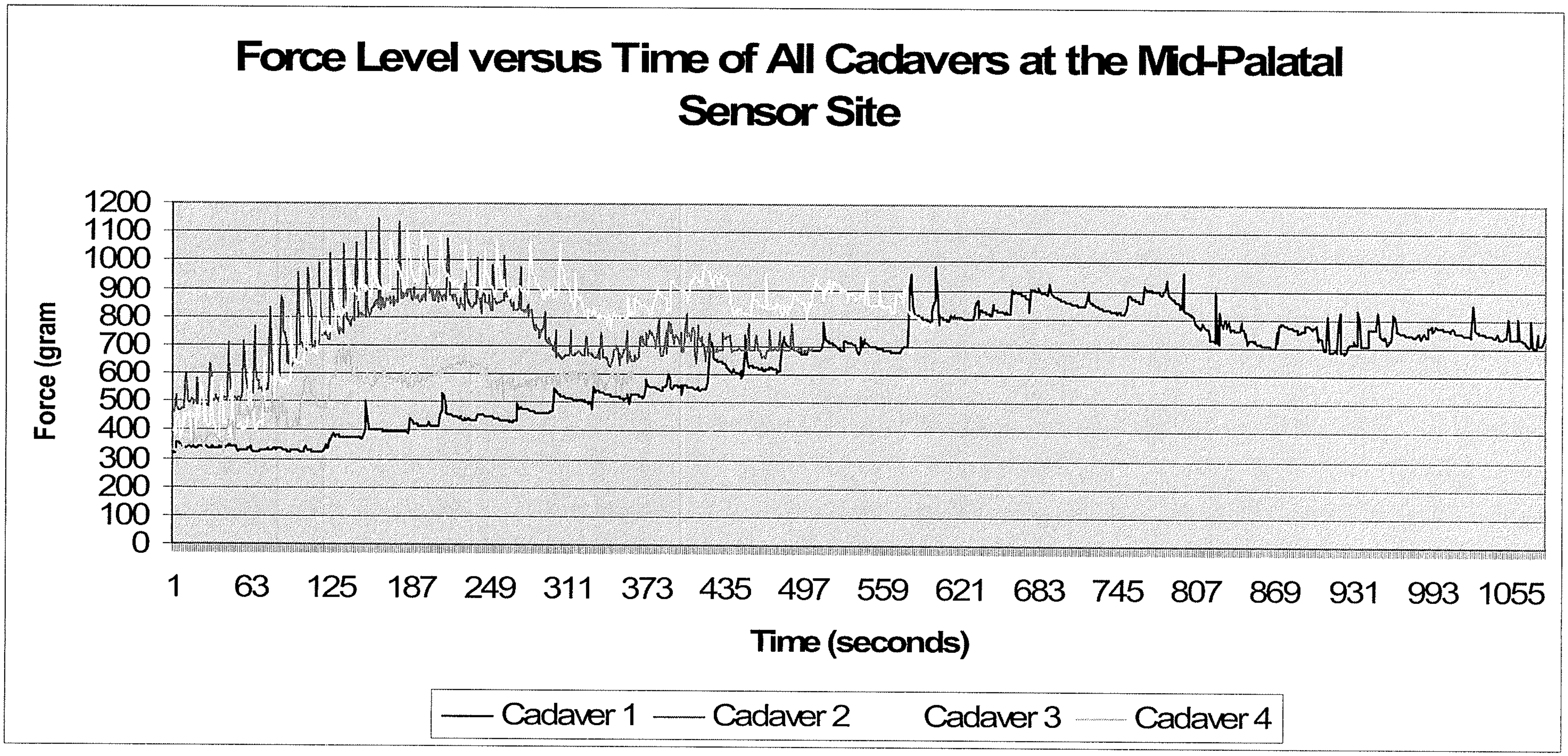



**Figure 16: Force level (grams) versus time (seconds) of mid-palatal suture for Cadavers 1-4**

### *5.6 Intermaxillary Suture Comparisons*

A comparison of the intermaxillary sensor site results of all cadavers tested (1 through 4) is displayed by Figure 17. It is apparent that Cadaver 4 produced the lowest force values while Cadaver 1, the highest. This is also described in Table 6. Although all cadavers appear distinct, it appears that aside from Cadaver 3, the rest appear to follow the same logarithmic trend in increasing force levels in the 2 phase of RME activation. Finally it is apparent that Cadaver 1 was the longest test to perform, while Cadaver 4 was the shortest.

Using the unpaired t-test, we find that there is no statistical significance between cadavers for the maximum and minimum force values obtained ($P<0.05$).

| | Maximum | Minimum | Difference |
|---|---|---|---|
| **Cadaver 1** | 862.89 | 111.58 | 751.31 |
| **Cadaver 2** | 835.84 | 357.22 | 478.62 |
| **Cadaver 3** | 792.49 | 199.55 | 592.94 |
| **Cadaver 4** | 548.77 | 312.63 | 236.14 |

**Table 6: Maximum and minimum force values (grams) of the intermaxillary sensor site for all cadavers**

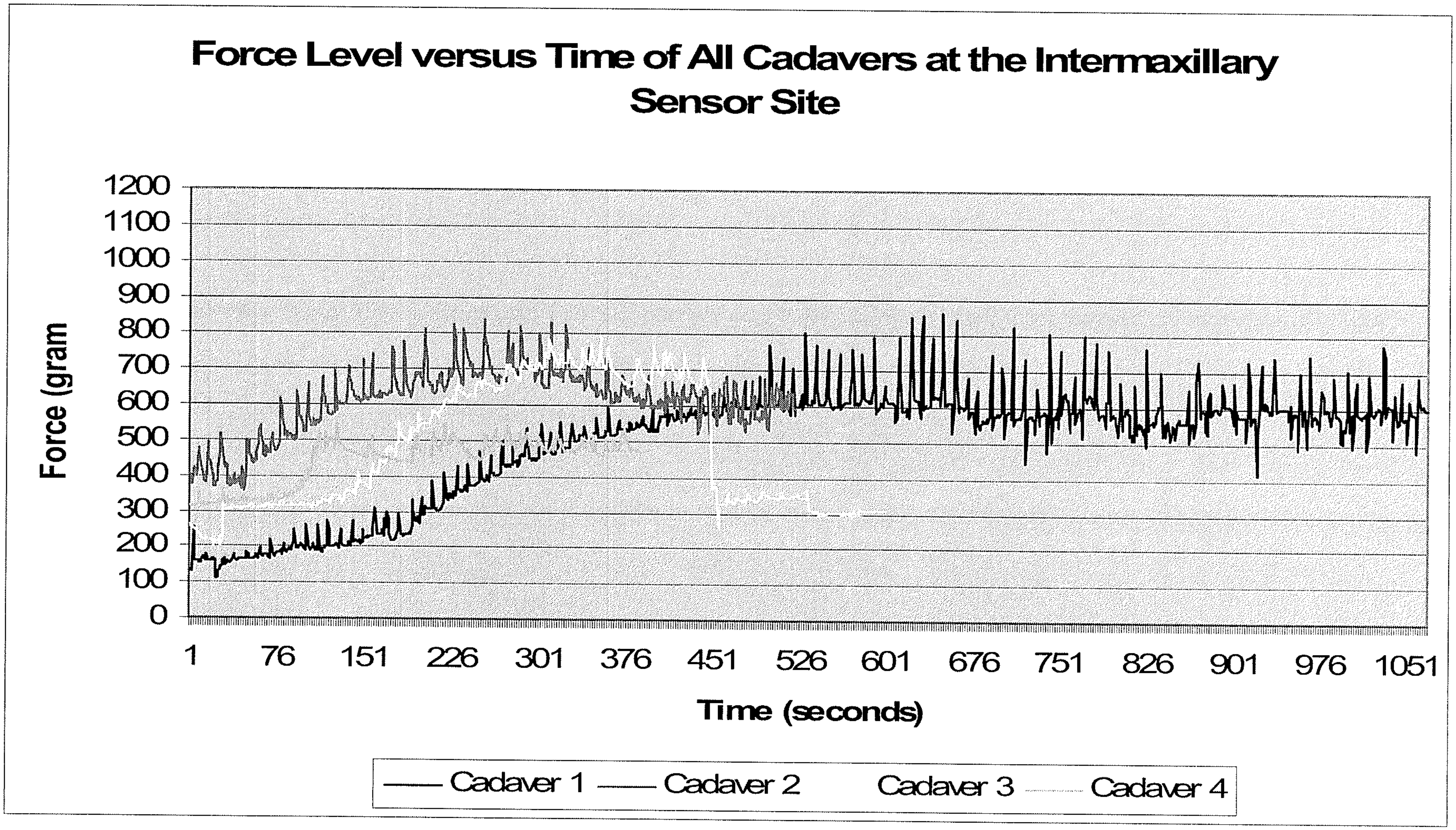



**Figure 17: Force level (grams) versus time (seconds) of intermaxillary suture for Cadavers 1-4**

### *5.7 Statistical Analysis of Maximum Force Values of both the Mid-Palatal and Intermaxillary Suture Sensors Sites*

Maximum force values of all cadavers were compared for statistical significant differences using a two-tailed, paired Student t-test. A paired t-test is used when each data point in one group corresponds to a matching data point in the other group. The paired t-test is used to investigate the relationship between two groups where there is a meaningful one-to-one correspondence between the data points in one group and those in the other, e.g. a variable measured at the same time points under experimental and control conditions. Two-tailed tests are used where there is no basis to assume that there may be a significant difference between the groups (Hassard, 1991). It was determined that there was a statistical significance of the maximum force values between the mid-palatal and intermaxillary sensor site at the 95% confidence interval ($p<0.05$).

# 6.0 DISCUSSION

## *6.1 Main Discussion*

Despite the extensive research of the effects of the RME appliance, this is the first study that measured the strain and force exerted directly on the bone in the human cadaver while activating an RME appliance.

Force values obtained for both the mid-palatal and intermaxillary sites exhibit values that were well within the range of orthopaedic values (over 500 grams). There were however differences between cadavers, as well as statistically significant differences due to different sites of measurement. The differences are understandable however, as there is individual variation from specimen to specimen. Each cadaver is unique, but follows a general trend of increasing force levels once the RME is activated. It can be postulated that these differences result from the individual variation between cadavers. Different cadavers have varying degrees of thickness of bone and soft tissues. Gender may also play a role in the different numbers, as the female cadavers were generally smaller than the male cadavers. Gender was not used in our analysis and as there was no objective way available to us to determine the hard and soft tissue thickness of each cadaver, accordingly we did not include that in our study. Some values did produce some anomalies in the graphing of the force versus time, specifically in Cadaver 3 and Cadaver 4. In Cadaver 3, at approximately 450 seconds, the RME appliance slipped off the Cadaver's oral cavity producing the jump as displayed in Figure 14. It was determined that the experiment did not have to be redone, as it took place in the end phase of the expansion. In Cadaver 4, there were some teeth that fractured as the expansion was taking place, and as a result, the graph does not follow a gradual increase over time, especially in the first part of the expansion (phase 1 and 2). It is not expected that in a living subject the same type of teeth fracture will occur, due to the elastic fibers in the living subjects, vitality of the PDL and blood supply.

The mid-palatal sensor reading displayed some interesting rises and drops near the beginning of activation of the RME appliance. This may be attributed to one of the teeth fracturing during activation at approximately that time.

All sutures were given a visual and tactile examination following complete activation which yielded in no sutures having disconnected from one another or fractured despite the 12 mm of activation of the RME appliance. The use of UV light could have provided a bit more insight into the status of the sutures, as was performed by Gardner in 1971, but we opted for only gross evaluation with the naked eye. Furthermore, histological sections could have confirmed the extent of obliteration of the mid-palatal suture as was performed by Melsen in 1975. It would have been interesting to compare our results to her study, however due to the Department of Anatomy's policy governing these cadavers, we were unable to carry this out, as the cadavers were required by other health-care disciplines for routine dissection. Future studies on recently deceased cadavers, prior to rigor mortis or embalming could give some more insight into the histological aspects, as live studies on humans would not be possible. Although these studies would be ideal, it is not expected that they would be necessary as the studies of Ten Cate and Freeman (1977) have extensively examined this subject in rats. That being said, it would be interesting to evaluate whether or not these specimens have sutures that are fused or if there is an ability to induce patency post-mortem with an RME.

When comparing the 2 sites of sensor placement specifically, it was noted the force levels at the mid-palatal sensor site produced statistically significant higher values than the intermaxillary sensor site. An analogy for this phenomenon is similar tat occurs during an earthquake. Although the epicentre has the highest value on the Richter scale, as you move away from the epicentre, the force of the earthquake weakens. This is exactly what happened in this study. Although not yet published, our study involved placement of more sensors at varying site throughout the craniofacial complex. It was found that those sensors that were placed further away from the RME device, the less amount it registered on the P3 measuring device. This confirms Isaacson's study from 1964, which gave similar findings. This gives more validity to the theory that orthopaedic forces can have an indirect effect on changes in the craniofacial skeleton through biochemical and/or cellular effects.

According to Buckland-Wright in 1978, sutures can absorb a considerable amount of energy, which is what we also found in our study. If this were not the case, the force levels would continue to increase higher and higher with no relaxation or fall in the values as time went on. Indeed there were general trends of increases over time, but they levelled off in all of our trials suggesting that not only the sutures, but the surrounding soft tissues play a role in force dissipation across the craniofacial osseous and non-osseus regions.

Despite the large forces exerted at these suture sites, no sutures were displaced or achieved patency in our study. Although a study by Wehrbein and Yildizhan (2001) analyzed the sutures of 18-38 year-old cadavers and found fusion had not actually occurred, our cadavers were much older. Also according to Wehrbein and Yildizhan, different patients exhibited different degrees of suture obliteration, so this variability should be accounted for when the clinician decides on using an RME for clinical practice. This was also found by Persson and Thilander in 1977 who actually found a 54 year-old subject without ossification. Furthermore, even if the mid-palatal suture did break, in elderly specimens, there is also resistance at the pterygomaxillary interface from the pterygoid plates of the sphenoid bones, which have a tendency to bend laterally and prevent the posterior area of the suture from opening (Wertz, 1970; Chaconas and Caputo, 1982; Jafari, Shetty and Kumar 2003). This resistance can further block any sutures from effectively opening and achieving orthopaedic expansion. This is why during SARPE procedures, the severance of the pterygomaxillary connection is necessary to properly achieve expansion. As the mode of action with RME appliances, the opening of the suture generally follows a fan-shape with larger opening in the anterior area and less in the posterior. This may indicate a higher force value in the anterior area or less resistance to expansion. This did not seem to be the case with our study, as the anterior area generated less force than posteriorly. Also, anatomy probably plays a role in this fan-shape expansion as there is only soft tissue anteriorly and posteriorly there are more hard tissue structures that can impede or lessen the effect of expansion, despite the force acting directly in the area. This probably accounts for the higher force generation in the palatal area.

From the study of Isaacson and coworkers in 1964, strain gauges in RME's found that large forces of 1.3-4.5 kg were achieved from single activations with rapid decay initially. Zimring and Isaacson (1965) found that these forces were even higher in another study (7.5-15.7 kg). Although our numbers did not produce values as high as these, it could be because Isaacson and coworkers put the sensor directly on the RME, whereas our sensor was directly on the bone. This difference can therefore be postulated that the force was dissipated by all surrounding structures, including hard and soft tissues.

In the photoelastic study of Chocanos and Caputo study of 1982, it was found that the stresses generated in the anterior region of the palate were higher and became less and less as one moved more posteriorly. This was not the case in our study as the forces generated in the anterior area were significantly less than the posterior area ($P<0.05$). The explanation for this could be that Chaconas's study involved a plastic simulation of a human skull and did not factor in the effect of soft tissue which our study controlled for. However, that being said, Chaconas et al found that the forces generated were orthopaedic in nature which was also found in our study. Regardless, it is considered appropriate to generate higher forces in older patients requiring RME so that the force can be used to achieve some orthopaedic change, as Isaacson described in 1964.

From the work of Oberheim and Mao in 2002, it was found that bone strain was higher in younger skulls than in older skulls. Using this study as an example, it would be fair to assume that the forces generated from our study would result in even higher force values in younger patients due to their bone being less stiff than adult bone and subject to greater deformation. However, according to the finite element analysis study of Holberg et al in 2006, they displayed higher cranial base stresses due to the decrease in elasticity of the adult skull versus the young skull.

Our study also agreed with the findings of Timms' (1980) research. We also found the stress to be greatest in the area it is being delivered, while further away, it diminishes.

### *6.2 Study Assumptions and Limitations*

Many assumptions were made while conducting this study. First and foremost, craniofacial orthopaedics is commonly attempted in the adolescent population and therefore a study on adolescent cadavers and dry skulls would be desirable. However they were not available for this study. Nevertheless, with the current upsurge in adult orthodontics, this study, despite the age of the cadavers, may have direct and important clinical applicability for dissipation of higher forces in general.

Secondly, we are making the assumption that the bone physiology of a cadaver that is fixed with formaldehyde will react similarly to that of a living subject. This is as close to the real situation as we are able to achieve.

Lastly, the sample size in this study could be considered relatively low. Performing this study involves many technique sensitive steps with sensors that were expensive and non-user-friendly which failed often. This combined with the fact that it requires 2 operators approximately 15 hours per cadaver to complete one study, makes it very time consuming. There was also a limit to the cadaveric material available at a short window of opportunity to conduct the experiment prior to dissection of the material by students.

The limitations in working with human cadavers include access to the important areas to be studied in the craniofacial skeleton. Achieving clear access to the RME appliance once fully seated was extremely difficult and required patience and determination to activate and turn the key for expansion.

## 7.0 CONCLUSIONS

**<u>Objective #1:</u>** To quantify the force levels generated at the mid-palatal suture during activation of the RME appliance.

> ***Null Hypothesis #1:*** There are no measurable force levels detectable at the mid-palatal suture after activation of the RME.

**<u>There is sufficient evidence to reject null hypotheses #1 because it was found that there were force levels detectable at the mid-palatal suture.</u>**

> ***Null Hypothesis #2:*** The force levels generated at the mid-palatal suture are not orthopaedic in nature (500 grams/16 oz or higher).

**<u>There is sufficient evidence to reject null hypotheses #2 because it was found that there the force levels were orthopaedic in nature, or over 500 grams.</u>**

> ***Null Hypothesis #3:*** The maximum force levels generated at the mid-palatal suture do not exhibit statistically significant differences between cadavers.

**<u>There is sufficient evidence to accept null hypotheses #3 because it was found that the maximum force levels did not differ with statistical significance at the mid-palatal suture between cadavers.</u>**

**<u>Objective #2:</u>** To quantify the force levels generated at the intermaxillary suture during activation of the RME appliance.

*Null Hypothesis #4:* There are no measurable force levels detectable at the intermaxillary suture after activation of the RME.

**There is sufficient evidence to reject null hypotheses #4 because it was found that there were force levels detectable at the intermaxillary suture.**

*Null Hypothesis #5:* The force levels generated at the intermaxillary suture are not orthopaedic in nature (500 grams/16 oz or higher).

**There is sufficient evidence to reject null hypotheses #5 because it was found that there the force levels were orthopaedic in nature, or over 500 grams.**

*Null Hypothesis #6:* The maximum force levels generated at the intermaxillary suture do not exhibit statistically significant differences between cadavers.

**There is sufficient evidence to accept null hypotheses #6 because it was found that the maximum force levels did not differ with statistical significance at the intermaxillary suture between cadavers.**

**Objective #3:** To determine if the mid-palatal suture remains fused or separates following activation of the RME appliance.

*Null Hypothesis #7:* The mid-palatal suture will not break following activation of the RME appliance due to the advanced age of the specimens.

**There is sufficient evidence to accept null hypotheses #7 because it was found that the mid-palatal suture did not break following activation of the RME appliance.**

## 8.0 REFERENCES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# 9.0 APPENDICES

## *9.1 Microsoft Excel Principal Strain Calculation Template*

| Pricipal Strain Calculation | | |
|---|---|---|
| | | |
| **Left Tube** | | |
| F_A | 45 | Lat |
| 0 | 0 | 1 |

| | | |
|---|---|---|
| Modulus of Elast. | 29000 | ksi |
| Poison's Ratio | 0.29 | |

| | | |
|---|---|---|
| Strain LH | $E_1$ | 0.0000E+00 |
| | $E_2$ | 0.0000E+00 |
| | $E_3$ | 1.0000E-06 |

| | | Actual | Micro |
|---|---|---|---|
| Princ. Strain Ep,q (ε) | P | 1.2E-06 | 1 |
| | Q | -2.1E-07 | 0 |

| | | | |
|---|---|---|---|
| Plain Stress (σ) | P | 0.0 | ksi |
| | Q | 0.0 | ksi |
| Shear Stress (τ) | Max. | 0.0 | ksi |
| | Mean | 4.7 | ksi |

| | | |
|---|---|---|
| Angle Θ (deg) | Calculated | 22.5 |
| | P | -67.5 |
| | Q | 22.5 |

## 9.2 *Complete Raw Data for Cadaver 1*

### *9.2.1 Mid-Palatal Suture Sensor*

| time | 1 | 2 | 3 |
|---|---|---|---|
| 1 | -3 | -3 | -2 |
| 2 | 2 | 1 | -3 |
| 3 | 6 | 3 | -6 |
| 4 | 15 | 92 | -565 |
| 5 | 13 | 71 | -481 |
| 6 | 12 | 73 | -484 |
| 7 | 11 | 74 | -482 |
| 8 | 9 | 44 | -294 |
| 9 | 9 | 42 | -293 |
| 10 | 9 | 41 | -293 |
| 11 | 9 | 41 | -290 |
| 12 | 8 | 41 | -291 |
| 13 | 8 | 41 | -292 |
| 14 | 2 | 38 | -290 |
| 15 | 6 | 34 | -246 |
| 16 | 5 | 31 | -243 |
| 17 | 1 | 32 | -243 |
| 18 | 6 | 34 | -244 |
| 19 | 7 | 32 | -243 |
| 20 | 5 | 32 | -242 |
| 21 | 3 | 31 | -241 |
| 22 | 3 | 32 | -241 |
| 23 | 3 | 32 | -241 |
| 24 | 3 | 32 | -241 |
| 25 | 3 | 33 | -241 |
| 26 | 2 | 33 | -241 |
| 27 | 2 | 33 | -241 |
| 28 | 3 | 33 | -240 |
| 29 | 3 | 33 | -241 |
| 30 | 8 | 33 | -242 |
| 31 | 13 | 36 | -262 |
| 32 | 7 | 36 | -270 |
| 33 | 16 | 37 | -295 |
| 34 | 8 | 42 | -278 |
| 35 | 7 | 39 | -246 |
| 36 | 5 | 38 | -245 |
| 37 | 2 | 36 | -244 |
| 38 | 5 | 22 | -224 |
| 39 | 3 | 38 | -255 |
| 40 | 3 | 37 | -257 |
| 41 | -9 | 34 | -261 |
| 42 | 9 | 43 | -269 |
| 43 | 2 | 37 | -259 |
| 44 | 5 | 35 | -276 |
| 45 | -5 | 40 | -275 |
| 46 | 6 | 40 | -310 |
| 47 | 3 | 45 | -302 |
| 48 | 3 | 47 | -304 |
| 49 | -1 | 44 | -295 |
| 50 | 1 | 49 | -303 |
| 51 | 2 | 50 | -297 |
| 52 | 19 | 53 | -294 |
| 53 | 10 | 50 | -285 |
| 54 | 10 | 49 | -284 |
| 55 | 10 | 49 | -284 |
| 56 | 10 | 49 | -283 |
| 57 | 10 | 49 | -284 |
| 58 | 9 | 50 | -284 |
| 59 | 9 | 50 | -284 |
| 60 | 7 | 44 | -269 |
| 61 | 7 | 43 | -280 |
| 62 | 0 | 42 | -284 |
| 63 | 22 | 42 | -299 |
| 64 | 33 | 49 | -312 |
| 65 | 30 | 66 | -373 |
| 66 | 30 | 60 | -359 |
| 67 | 29 | 58 | -357 |
| 68 | 28 | 58 | -353 |
| 69 | 28 | 58 | -353 |
| 70 | 27 | 58 | -353 |
| 71 | 27 | 58 | -353 |
| 72 | 26 | 58 | -353 |
| 73 | 26 | 58 | -353 |
| 74 | 26 | 58 | -353 |
| 75 | 20 | 55 | -350 |
| 76 | 22 | 57 | -352 |
| 77 | 23 | 56 | -350 |
| 78 | 24 | 57 | -351 |
| 79 | 24 | 57 | -350 |
| 80 | 20 | 52 | -354 |
| 81 | 21 | 53 | -351 |
| 82 | 22 | 52 | -334 |
| 83 | 18 | 46 | -322 |
| 84 | 17 | 41 | -304 |
| 85 | 21 | 49 | -350 |
| 86 | 21 | 43 | -312 |
| 87 | 20 | 38 | -287 |
| 88 | 20 | 38 | -281 |
| 89 | 20 | 37 | -277 |
| 90 | 24 | 44 | -300 |
| 91 | 43 | 46 | -288 |
| 92 | 43 | 52 | -303 |
| 93 | 40 | 52 | -321 |
| 94 | 41 | 44 | -242 |
| 95 | 43 | 54 | -300 |
| 96 | 45 | 56 | -298 |
| 97 | 45 | 56 | -298 |
| 98 | 45 | 56 | -299 |
| 99 | 44 | 56 | -299 |
| 100 | 43 | 48 | -289 |
| 101 | 43 | 43 | -298 |
| 102 | 47 | 51 | -333 |
| 103 | 48 | 50 | -314 |
| 104 | 47 | 42 | -282 |
| 105 | 46 | 36 | -155 |
| 106 | 43 | 34 | -220 |
| 107 | 43 | 36 | -229 |
| 108 | 41 | 35 | -231 |
| 109 | 42 | 32 | -222 |
| 110 | 40 | 30 | -222 |
| 111 | 40 | 31 | -229 |
| 112 | 40 | 30 | -225 |
| 113 | 40 | 29 | -220 |
| 114 | 39 | 27 | -214 |
| 115 | 39 | 27 | -214 |
| 116 | 38 | 27 | -212 |
| 117 | 37 | 28 | -217 |
| 118 | 39 | 32 | -231 |
| 119 | 37 | 33 | -231 |
| 120 | 49 | 33 | -254 |
| 121 | 79 | 39 | -278 |
| 122 | 57 | 35 | -267 |
| 123 | 62 | 47 | -304 |
| 124 | 60 | 49 | -130 |
| 125 | 55 | 48 | -134 |
| 126 | 67 | 46 | -132 |
| 127 | 83 | 38 | -117 |
| 128 | 78 | 50 | -167 |
| 129 | 79 | 53 | -168 |
| 130 | 79 | 54 | -169 |
| 131 | 78 | 54 | -168 |
| 132 | 77 | 54 | -168 |
| 133 | 76 | 55 | -168 |
| 134 | 75 | 55 | -168 |
| 135 | 74 | 55 | -168 |
| 136 | 74 | 55 | -168 |
| 137 | 73 | 56 | -168 |
| 138 | 73 | 56 | -167 |
| 139 | 72 | 56 | -167 |
| 140 | 72 | 56 | -167 |
| 141 | 71 | 57 | -167 |
| 142 | 71 | 57 | -166 |
| 143 | 71 | 57 | -166 |
| 144 | 70 | 57 | -165 |
| 145 | 70 | 56 | -162 |
| 146 | 68 | 62 | -180 |
| 147 | 70 | 64 | -185 |
| 148 | 68 | 64 | -183 |
| 149 | 66 | 59 | -169 |
| 150 | 65 | 57 | -166 |
| 151 | 82 | 46 | -145 |
| 152 | 93 | 52 | -123 |
| 153 | 106 | 13 | 51 |
| 154 | 109 | 27 | -13 |
| 155 | 100 | 49 | -137 |
| 156 | 95 | 56 | -132 |
| 157 | 99 | 61 | -160 |
| 158 | 101 | 59 | -159 |
| 159 | 100 | 62 | -165 |
| 160 | 99 | 63 | -165 |
| 161 | 98 | 63 | -164 |
| 162 | 97 | 63 | -163 |
| 163 | 96 | 63 | -162 |
| 164 | 95 | 63 | -161 |
| 165 | 94 | 63 | -160 |
| 166 | 93 | 63 | -159 |
| 167 | 93 | 63 | -159 |
| 168 | 92 | 63 | -159 |
| 169 | 91 | 63 | -159 |
| 170 | 91 | 63 | -159 |
| 171 | 90 | 63 | -159 |
| 172 | 89 | 63 | -159 |
| 173 | 89 | 63 | -158 |
| 174 | 89 | 64 | -158 |
| 175 | 88 | 64 | -158 |
| 176 | 88 | 64 | -158 |
| 177 | 87 | 64 | -158 |
| 178 | 87 | 65 | -158 |
| 179 | 87 | 65 | -158 |
| 180 | 86 | 65 | -158 |
| 181 | 86 | 65 | -158 |
| 182 | 85 | 65 | -158 |
| 183 | 85 | 65 | -158 |
| 184 | 84 | 65 | -158 |
| 185 | 84 | 64 | -151 |
| 186 | 84 | 61 | -158 |
| 187 | 142 | 50 | -162 |
| 188 | 135 | 52 | -156 |
| 189 | 132 | 62 | -163 |
| 190 | 122 | 63 | -166 |
| 191 | 120 | 65 | -169 |
| 192 | 119 | 65 | -171 |
| 193 | 118 | 65 | -170 |
| 194 | 116 | 65 | -167 |
| 195 | 115 | 65 | -167 |
| 196 | 114 | 65 | -167 |
| 197 | 113 | 65 | -167 |
| 198 | 112 | 65 | -167 |
| 199 | 111 | 65 | -167 |
| 200 | 110 | 65 | -167 |
| 201 | 108 | 59 | -122 |
| 202 | 106 | 50 | -58 |
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| 1490 | 338 | 197 | -367 |
| 1491 | 338 | 197 | -367 |
| 1492 | 337 | 197 | -367 |
| 1493 | 337 | 197 | -367 |
| 1494 | 337 | 197 | -367 |
| 1495 | 337 | 197 | -367 |
| 1496 | 336 | 197 | -367 |
| 1497 | 345 | 198 | -444 |
| 1498 | 350 | 198 | -374 |
| 1499 | 354 | 198 | -394 |
| 1500 | 346 | 200 | -366 |
| 1501 | 344 | 200 | -387 |
| 1502 | 353 | 208 | -376 |
| 1503 | 341 | 206 | -422 |
| 1504 | 337 | 215 | -409 |
| 1505 | 336 | 206 | -377 |
| 1506 | 334 | 202 | -373 |
| 1507 | 337 | 203 | -397 |
| 1508 | 332 | 212 | -401 |
| 1509 | 331 | 213 | -397 |
| 1510 | 334 | 213 | -388 |
| 1511 | 333 | 212 | -386 |
| 1512 | 333 | 212 | -385 |
| 1513 | 321 | 211 | -406 |
| 1514 | 334 | 199 | -415 |
| 1515 | 337 | 192 | -379 |
| 1516 | 328 | 183 | -339 |
| 1517 | 327 | 179 | -332 |
| 1518 | 329 | 180 | -333 |
| 1519 | 326 | 177 | -311 |
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### *9.2.2 Intermaxillary Suture Sensor*

| time | 1 | 2 | 3 |
|---|---|---|---|
| 1 | -1 | 1 | 0 |
| 2 | -3 | -1 | -7 |
| 3 | -4 | -1 | -8 |
| 4 | 31 | 108 | 48 |
| 5 | -9 | 26 | 15 |
| 6 | -7 | 22 | 15 |
| 7 | -6 | 21 | 15 |
| 8 | -6 | 21 | 15 |
| 9 | -6 | 19 | 14 |
| 10 | -7 | 18 | 13 |
| 11 | -5 | 22 | 15 |
| 12 | -1 | 31 | 18 |
| 13 | -4 | 26 | 18 |
| 14 | -5 | 21 | 15 |
| 15 | 2 | 40 | 20 |
| 16 | -3 | 22 | 18 |
| 17 | -4 | 20 | 18 |
| 18 | -4 | 21 | 18 |
| 19 | -4 | 20 | 17 |
| 20 | -3 | 22 | 19 |
| 21 | -4 | 20 | 16 |
| 22 | -3 | 23 | 19 |
| 23 | -6 | 21 | 14 |
| 24 | -23 | -3 | -39 |
| 25 | -19 | -8 | -34 |
| 26 | -14 | 8 | -13 |
| 27 | -13 | 9 | -8 |
| 28 | -11 | 12 | -5 |
| 29 | -8 | 17 | 1 |
| 30 | -7 | 24 | 8 |
| 31 | -5 | 30 | 11 |
| 32 | -8 | 18 | 4 |
| 33 | -6 | 22 | 8 |
| 34 | -6 | 23 | 9 |
| 35 | -7 | 22 | 7 |
| 36 | -7 | 21 | 7 |
| 37 | -7 | 23 | 11 |
| 38 | -6 | 24 | 11 |
| 39 | -2 | 40 | 16 |
| 40 | -4 | 31 | 13 |
| 41 | -6 | 24 | 12 |
| 42 | -7 | 23 | 15 |
| 43 | -5 | 25 | 19 |
| 44 | -6 | 26 | 19 |
| 45 | -5 | 28 | 21 |
| 46 | -6 | 28 | 19 |
| 47 | -5 | 28 | 21 |
| 48 | -6 | 27 | 22 |
| 49 | -5 | 26 | 22 |
| 50 | -3 | 40 | 27 |
| 51 | 4 | 33 | 24 |
| 52 | -4 | 26 | 21 |
| 53 | -5 | 26 | 21 |
| 54 | -5 | 26 | 22 |
| 55 | -5 | 26 | 23 |
| 56 | -5 | 26 | 23 |
| 57 | -5 | 27 | 24 |
| 58 | -4 | 32 | 27 |
| 59 | -6 | 24 | 24 |
| 60 | -6 | 27 | 24 |
| 61 | 2 | 48 | 36 |
| 62 | -7 | 33 | 27 |
| 63 | -5 | 30 | 27 |
| 64 | -6 | 30 | 26 |
| 65 | -5 | 31 | 29 |
| 66 | -5 | 32 | 32 |
| 67 | -5 | 33 | 32 |
| 68 | -4 | 32 | 32 |
| 69 | -9 | 20 | 29 |
| 70 | -12 | 16 | 27 |
| 71 | 8 | 71 | 47 |
| 72 | 1 | 45 | 38 |
| 73 | -2 | 38 | 35 |
| 74 | -3 | 24 | 28 |
| 75 | 0 | 30 | 31 |
| 76 | -1 | 33 | 35 |
| 77 | -1 | 35 | 36 |
| 78 | -2 | 34 | 36 |
| 79 | -1 | 36 | 36 |
| 80 | 0 | 38 | 37 |
| 81 | 0 | 34 | 32 |
| 82 | 6 | 52 | 51 |
| 83 | -1 | 37 | 38 |
| 84 | 0 | 35 | 38 |
| 85 | 0 | 37 | 39 |
| 86 | 0 | 37 | 40 |
| 87 | 1 | 42 | 44 |
| 88 | 0 | 38 | 41 |
| 89 | 5 | 44 | 44 |
| 90 | 9 | 62 | 54 |
| 91 | 15 | 90 | 76 |
| 92 | 1 | 46 | 46 |
| 93 | 1 | 45 | 46 |
| 94 | 1 | 44 | 47 |
| 95 | 2 | 44 | 47 |

| | | | |
|---|---|---|---|
| 96 | 1 | 43 | 48 |
| 97 | 3 | 49 | 52 |
| 98 | 3 | 48 | 48 |
| 99 | -12 | 26 | 51 |
| 100 | -6 | 28 | 44 |
| 101 | 18 | 104 | 77 |
| 102 | 6 | 58 | 52 |
| 103 | 4 | 48 | 49 |
| 104 | 2 | 35 | 44 |
| 105 | 3 | 40 | 48 |
| 106 | 3 | 41 | 46 |
| 107 | 7 | 52 | 53 |
| 108 | 4 | 45 | 53 |
| 109 | -2 | 36 | 41 |
| 110 | -4 | 41 | 45 |
| 111 | 0 | 35 | 43 |
| 112 | 11 | 101 | 82 |
| 113 | 0 | 47 | 45 |
| 114 | 1 | 41 | 41 |
| 115 | 1 | 32 | 39 |
| 116 | 3 | 41 | 45 |
| 117 | 2 | 42 | 45 |
| 118 | 4 | 49 | 48 |
| 119 | 6 | 47 | 51 |
| 120 | 21 | 115 | 79 |
| 121 | 3 | 92 | 70 |
| 122 | 1 | 47 | 47 |
| 123 | 1 | 46 | 48 |
| 124 | 0 | 46 | 49 |
| 125 | 0 | 44 | 48 |
| 126 | 1 | 46 | 48 |
| 127 | 2 | 54 | 54 |
| 128 | 3 | 53 | 51 |
| 129 | -2 | 39 | 45 |
| 130 | 1 | 47 | 48 |
| 131 | 10 | 95 | 71 |
| 132 | 4 | 57 | 51 |
| 133 | 2 | 49 | 48 |
| 134 | 2 | 48 | 47 |
| 135 | 2 | 48 | 49 |
| 136 | 2 | 48 | 49 |
| 137 | 1 | 48 | 50 |
| 138 | 5 | 58 | 54 |
| 139 | 3 | 55 | 52 |
| 140 | 1 | 47 | 47 |
| 141 | 10 | 112 | 82 |
| 142 | 4 | 63 | 54 |
| 143 | 5 | 63 | 55 |
| 144 | 5 | 63 | 56 |
| 145 | 4 | 60 | 54 |
| 146 | 4 | 60 | 54 |
| 147 | 5 | 64 | 57 |
| 148 | 3 | 54 | 52 |
| 149 | 2 | 56 | 55 |
| 150 | 4 | 98 | 64 |
| 151 | 4 | 72 | 58 |
| 152 | 6 | 74 | 60 |
| 153 | 5 | 73 | 54 |
| 154 | 6 | 73 | 64 |
| 155 | 5 | 70 | 63 |
| 156 | 5 | 75 | 65 |
| 157 | 5 | 75 | 65 |
| 158 | 4 | 76 | 64 |
| 159 | 7 | 92 | 74 |
| 160 | 5 | 150 | 91 |
| 161 | 18 | 148 | 95 |
| 162 | 6 | 89 | 67 |
| 163 | 5 | 83 | 64 |
| 164 | 6 | 84 | 63 |
| 165 | 5 | 81 | 65 |
| 166 | 4 | 82 | 63 |
| 167 | 8 | 97 | 67 |
| 168 | 2 | 81 | 59 |
| 169 | 9 | 126 | 80 |
| 170 | 1 | 102 | 72 |
| 171 | 5 | 137 | 94 |
| 172 | 5 | 129 | 80 |
| 173 | 3 | 89 | 57 |
| 174 | -5 | 77 | 49 |
| 175 | -6 | 74 | 49 |
| 176 | -4 | 76 | 48 |
| 177 | -4 | 76 | 49 |
| 178 | -3 | 83 | 52 |
| 179 | -3 | 86 | 52 |
| 180 | -3 | 103 | 61 |
| 181 | 1 | 142 | 82 |
| 182 | -6 | 100 | 58 |
| 183 | -5 | 91 | 55 |
| 184 | -3 | 92 | 56 |
| 185 | -4 | 90 | 52 |
| 186 | -2 | 92 | 54 |
| 187 | -1 | 93 | 53 |
| 188 | -3 | 92 | 53 |
| 189 | -2 | 92 | 51 |
| 190 | 0 | 96 | 57 |
| 191 | -4 | 92 | 57 |
| 192 | -1 | 112 | 67 |
| 193 | -5 | 176 | 114 |
| 194 | 4 | 154 | 87 |
| 195 | 4 | 132 | 76 |
| 196 | 4 | 126 | 73 |
| 197 | 5 | 137 | 79 |
| 198 | -1 | 126 | 75 |
| 199 | 0 | 120 | 70 |
| 200 | -1 | 141 | 88 |
| 201 | -11 | 191 | 105 |
| 202 | 1 | 142 | 81 |
| 203 | 2 | 144 | 82 |
| 204 | 6 | 159 | 96 |
| 205 | 4 | 158 | 90 |
| 206 | 4 | 156 | 92 |
| 207 | 4 | 156 | 89 |

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| 210 | 3 | 223 | 144 |
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| 212 | 8 | 158 | 92 |
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| 215 | 3 | 149 | 90 |
| 216 | 2 | 149 | 90 |
| 217 | 3 | 154 | 95 |
| 218 | 3 | 155 | 94 |
| 219 | 4 | 173 | 100 |
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| 222 | 8 | 183 | 107 |
| 223 | 6 | 178 | 104 |
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| 231 | 7 | 260 | 158 |
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| 238 | 17 | 212 | 128 |
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| 240 | 8 | 200 | 120 |
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| 243 | 7 | 215 | 129 |
| 244 | 6 | 212 | 129 |
| 245 | 10 | 216 | 127 |
| 246 | 8 | 213 | 127 |
| 247 | 10 | 215 | 130 |
| 248 | 9 | 219 | 134 |
| 249 | 10 | 219 | 130 |
| 250 | 12 | 227 | 134 |
| 251 | 12 | 294 | 186 |
| 252 | 8 | 233 | 139 |
| 253 | 8 | 228 | 137 |
| 254 | 8 | 228 | 137 |
| 255 | 7 | 225 | 135 |
| 256 | 9 | 230 | 139 |
| 257 | 12 | 243 | 141 |
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| 261 | 6 | 248 | 144 |
| 262 | 8 | 247 | 145 |
| 263 | 10 | 245 | 142 |
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| 268 | 10 | 248 | 144 |
| 269 | 11 | 289 | 171 |
| 270 | 8 | 336 | 185 |
| 271 | 10 | 276 | 153 |
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| 273 | 10 | 268 | 151 |
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| 275 | 10 | 270 | 156 |
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| 277 | 10 | 272 | 154 |
| 278 | 11 | 272 | 157 |
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| 281 | 7 | 278 | 160 |
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| 284 | 1 | 270 | 151 |
| 285 | 9 | 281 | 151 |
| 286 | 9 | 298 | 161 |
| 287 | 11 | 306 | 163 |
| 288 | 10 | 298 | 163 |
| 289 | 8 | 295 | 166 |
| 290 | 6 | 293 | 164 |
| 291 | 9 | 370 | 197 |
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| 293 | 5 | 297 | 160 |
| 294 | 4 | 291 | 157 |
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| 296 | 3 | 288 | 159 |
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| 298 | 5 | 288 | 158 |
| 299 | 3 | 287 | 158 |
| 300 | 8 | 294 | 161 |
| 301 | 8 | 288 | 160 |
| 302 | 15 | 341 | 186 |
| 303 | 15 | 364 | 192 |
| 304 | 25 | 386 | 190 |
| 305 | 12 | 314 | 164 |
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| 308 | 12 | 310 | 163 |
| 309 | 14 | 310 | 163 |
| 310 | 16 | 317 | 168 |
| 311 | 26 | 356 | 195 |
| 312 | 13 | 306 | 164 |
| 313 | 13 | 305 | 161 |
| 314 | 12 | 303 | 161 |
| 315 | 13 | 302 | 162 |
| 316 | 15 | 315 | 169 |
| 317 | 15 | 320 | 169 |
| 318 | 16 | 322 | 172 |
| 319 | 25 | 380 | 203 |

| | | | |
|---|---|---|---|
| 320 | 19 | 389 | 200 |
| 321 | 7 | 312 | 171 |
| 322 | 8 | 309 | 166 |
| 323 | 12 | 313 | 168 |
| 324 | 16 | 317 | 174 |
| 325 | 7 | 307 | 171 |
| 326 | 14 | 314 | 173 |
| 327 | 16 | 316 | 177 |
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| 329 | 16 | 326 | 181 |
| 330 | 11 | 375 | 218 |
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| 332 | 8 | 337 | 193 |
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| 334 | 9 | 333 | 192 |
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| 337 | 17 | 350 | 189 |
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| 339 | 10 | 335 | 194 |
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| 341 | -13 | 368 | 223 |
| 342 | 5 | 342 | 197 |
| 343 | 7 | 340 | 196 |
| 344 | 7 | 339 | 194 |
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| 346 | 9 | 339 | 192 |
| 347 | 9 | 339 | 194 |
| 348 | 11 | 343 | 198 |
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| 353 | 0 | 343 | 198 |
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| 355 | 2 | 343 | 197 |
| 356 | 4 | 345 | 197 |
| 357 | 4 | 344 | 196 |
| 358 | 8 | 350 | 200 |
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| 360 | 4 | 357 | 205 |
| 361 | 3 | 424 | 237 |
| 362 | -5 | 357 | 205 |
| 363 | -2 | 355 | 202 |
| 364 | -3 | 353 | 202 |
| 365 | -2 | 352 | 202 |
| 366 | -2 | 351 | 202 |
| 367 | -3 | 350 | 203 |
| 368 | -4 | 350 | 202 |
| 369 | -2 | 356 | 202 |
| 370 | 3 | 370 | 207 |
| 371 | -16 | 397 | 212 |
| 372 | -7 | 369 | 203 |
| 373 | -5 | 368 | 204 |
| 374 | -10 | 362 | 200 |
| 375 | -11 | 360 | 186 |
| 376 | -7 | 364 | 193 |
| 377 | -8 | 365 | 198 |
| 378 | -3 | 371 | 202 |
| 379 | -4 | 370 | 199 |
| 380 | 0 | 386 | 214 |
| 381 | -9 | 386 | 206 |
| 382 | -11 | 373 | 201 |
| 383 | -10 | 373 | 201 |
| 384 | -10 | 373 | 202 |
| 385 | -9 | 378 | 204 |
| 386 | -7 | 391 | 207 |
| 387 | -8 | 383 | 206 |
| 388 | -9 | 378 | 204 |
| 389 | -7 | 383 | 207 |
| 390 | -11 | 384 | 218 |
| 391 | -18 | 413 | 220 |
| 392 | -18 | 385 | 208 |
| 393 | -17 | 384 | 209 |
| 394 | -17 | 384 | 207 |
| 395 | -15 | 382 | 197 |
| 396 | -27 | 374 | 200 |
| 397 | -25 | 377 | 194 |
| 398 | -25 | 384 | 191 |
| 399 | -25 | 435 | 227 |
| 400 | -39 | 383 | 191 |
| 401 | -36 | 381 | 192 |
| 402 | -31 | 384 | 193 |
| 403 | -32 | 383 | 192 |
| 404 | -29 | 391 | 197 |
| 405 | -22 | 414 | 202 |
| 406 | -22 | 409 | 200 |
| 407 | -15 | 420 | 205 |
| 408 | -13 | 417 | 210 |
| 409 | -20 | 419 | 207 |
| 410 | -18 | 419 | 206 |
| 411 | -15 | 431 | 214 |
| 412 | -43 | 447 | 219 |
| 413 | -27 | 401 | 195 |
| 414 | -26 | 416 | 204 |
| 415 | -21 | 420 | 214 |
| 416 | -20 | 422 | 216 |
| 417 | -19 | 420 | 214 |
| 418 | -26 | 412 | 202 |
| 419 | -26 | 413 | 202 |
| 420 | -24 | 413 | 205 |
| 421 | -15 | 438 | 210 |
| 422 | -58 | 421 | 235 |
| 423 | -33 | 417 | 204 |
| 424 | -18 | 432 | 205 |
| 425 | -18 | 432 | 205 |
| 426 | -18 | 431 | 205 |
| 427 | -22 | 427 | 199 |
| 428 | -22 | 426 | 198 |
| 429 | -24 | 412 | 201 |
| 430 | -19 | 436 | 202 |
| 431 | -23 | 428 | 196 |

| | | | |
|---|---|---|---|
| 432 | -64 | 446 | 234 |
| 433 | -32 | 437 | 202 |
| 434 | -31 | 436 | 202 |
| 435 | -32 | 433 | 199 |
| 436 | -28 | 440 | 214 |
| 437 | -34 | 428 | 197 |
| 438 | -35 | 427 | 195 |
| 439 | -33 | 439 | 211 |
| 440 | -30 | 448 | 201 |
| 441 | -29 | 472 | 239 |
| 442 | -44 | 459 | 212 |
| 443 | -37 | 445 | 201 |
| 444 | -38 | 442 | 199 |
| 445 | -38 | 441 | 199 |
| 446 | -37 | 442 | 199 |
| 447 | -38 | 442 | 198 |
| 448 | -39 | 440 | 196 |
| 449 | -51 | 427 | 196 |
| 450 | -40 | 444 | 212 |
| 451 | -63 | 438 | 206 |
| 452 | -35 | 446 | 195 |
| 453 | -70 | 438 | 205 |
| 454 | -86 | 447 | 246 |
| 455 | -74 | 416 | 220 |
| 456 | -43 | 434 | 196 |
| 457 | -43 | 435 | 196 |
| 458 | -42 | 437 | 196 |
| 459 | -43 | 436 | 198 |
| 460 | -42 | 442 | 199 |
| 461 | -26 | 486 | 224 |
| 462 | -60 | 442 | 243 |
| 463 | -38 | 471 | 202 |
| 464 | -40 | 456 | 199 |
| 465 | -38 | 456 | 196 |
| 466 | -37 | 458 | 201 |
| 467 | -36 | 458 | 200 |
| 468 | -32 | 479 | 205 |
| 469 | -39 | 461 | 210 |
| 470 | -32 | 486 | 209 |
| 471 | -134 | 460 | 269 |
| 472 | -70 | 469 | 216 |
| 473 | -50 | 466 | 204 |
| 474 | -49 | 465 | 205 |
| 475 | -50 | 463 | 205 |
| 476 | -49 | 463 | 203 |
| 477 | -49 | 462 | 204 |
| 478 | -44 | 480 | 211 |
| 479 | -36 | 533 | 232 |
| 480 | -95 | 457 | 232 |
| 481 | -57 | 465 | 205 |
| 482 | -55 | 465 | 204 |
| 483 | -57 | 463 | 204 |
| 484 | -55 | 464 | 208 |
| 485 | -55 | 463 | 205 |
| 486 | -56 | 463 | 207 |
| 487 | -56 | 463 | 206 |
| 488 | -53 | 472 | 213 |
| 489 | -81 | 476 | 214 |
| 490 | -56 | 461 | 203 |
| 491 | -75 | 503 | 244 |
| 492 | -62 | 535 | 266 |
| 493 | -90 | 470 | 226 |
| 494 | -66 | 468 | 211 |
| 495 | -63 | 470 | 208 |
| 496 | -66 | 468 | 209 |
| 497 | -64 | 468 | 208 |
| 498 | -66 | 468 | 212 |
| 499 | -63 | 476 | 212 |
| 500 | -68 | 476 | 215 |
| 501 | -75 | 634 | 296 |
| 502 | -47 | 545 | 259 |
| 503 | -72 | 484 | 213 |
| 504 | -74 | 480 | 216 |
| 505 | -72 | 480 | 211 |
| 506 | -73 | 478 | 215 |
| 507 | -73 | 478 | 212 |
| 508 | -76 | 475 | 214 |
| 509 | -73 | 486 | 217 |
| 510 | -76 | 484 | 214 |
| 511 | -66 | 522 | 225 |
| 512 | -74 | 587 | 298 |
| 513 | -107 | 453 | 231 |
| 514 | -87 | 475 | 215 |
| 515 | -87 | 473 | 212 |
| 516 | -85 | 474 | 212 |
| 517 | -84 | 475 | 211 |
| 518 | -88 | 442 | 219 |
| 519 | -112 | 452 | 215 |
| 520 | -70 | 580 | 253 |
| 521 | -78 | 550 | 277 |
| 522 | -104 | 449 | 214 |
| 523 | -92 | 474 | 211 |
| 524 | -92 | 475 | 213 |
| 525 | -93 | 473 | 213 |
| 526 | -95 | 472 | 215 |
| 527 | -97 | 481 | 221 |
| 528 | -90 | 504 | 239 |
| 529 | -109 | 467 | 219 |
| 530 | -96 | 486 | 225 |
| 531 | -85 | 657 | 327 |
| 532 | -126 | 523 | 293 |
| 533 | -101 | 484 | 220 |
| 534 | -103 | 482 | 221 |
| 535 | -101 | 483 | 219 |
| 536 | -104 | 480 | 222 |
| 537 | -103 | 481 | 219 |
| 538 | -101 | 489 | 229 |
| 539 | -104 | 487 | 226 |
| 540 | -100 | 504 | 228 |
| 541 | -78 | 639 | 294 |
| 542 | -154 | 521 | 271 |
| 543 | -125 | 486 | 220 |
| 544 | -114 | 485 | 221 |
| 545 | -112 | 485 | 220 |
| 546 | -114 | 483 | 221 |
| 547 | -113 | 483 | 220 |
| 548 | -113 | 483 | 219 |
| 549 | -115 | 495 | 231 |
| 550 | -108 | 512 | 233 |
| 551 | -103 | 622 | 306 |
| 552 | -171 | 494 | 272 |
| 553 | -119 | 480 | 221 |
| 554 | -122 | 476 | 222 |
| 555 | -122 | 476 | 219 |
| 556 | -121 | 478 | 222 |
| 557 | -122 | 477 | 219 |
| 558 | -122 | 476 | 222 |
| 559 | -130 | 482 | 222 |
| 560 | -108 | 528 | 233 |
| 561 | -166 | 600 | 340 |
| 562 | -141 | 470 | 227 |
| 563 | -125 | 491 | 218 |
| 564 | -126 | 491 | 220 |
| 565 | -124 | 493 | 221 |
| 566 | -124 | 492 | 220 |
| 567 | -124 | 493 | 223 |
| 568 | -121 | 495 | 221 |
| 569 | -123 | 491 | 225 |
| 570 | -124 | 508 | 246 |
| 571 | -104 | 570 | 253 |
| 572 | -160 | 614 | 339 |
| 573 | -121 | 518 | 237 |
| 574 | -114 | 490 | 216 |
| 575 | -115 | 490 | 218 |
| 576 | -115 | 490 | 215 |
| 577 | -116 | 489 | 215 |
| 578 | -114 | 490 | 218 |
| 579 | -114 | 490 | 215 |
| 580 | -113 | 499 | 227 |
| 581 | -92 | 623 | 269 |
| 582 | -118 | 499 | 252 |
| 583 | -113 | 508 | 220 |
| 584 | -116 | 504 | 216 |
| 585 | -116 | 504 | 217 |
| 586 | -116 | 503 | 214 |
| 587 | -120 | 499 | 213 |
| 588 | -119 | 500 | 215 |
| 589 | -123 | 506 | 224 |
| 590 | -111 | 541 | 229 |
| 591 | -111 | 661 | 312 |
| 592 | -142 | 472 | 201 |
| 593 | -138 | 478 | 211 |
| 594 | -138 | 479 | 213 |
| 595 | -137 | 480 | 209 |
| 596 | -128 | 489 | 218 |
| 597 | -125 | 494 | 227 |
| 598 | -134 | 483 | 218 |
| 599 | -143 | 490 | 220 |
| 600 | -129 | 529 | 257 |
| 601 | -111 | 516 | 222 |
| 602 | -119 | 495 | 213 |
| 603 | -118 | 498 | 213 |
| 604 | -120 | 497 | 212 |
| 605 | -118 | 498 | 214 |
| 606 | -118 | 499 | 215 |
| 607 | -118 | 498 | 213 |
| 608 | -134 | 487 | 226 |
| 609 | -143 | 425 | 224 |
| 610 | -141 | 448 | 213 |
| 611 | -137 | 477 | 226 |
| 612 | -84 | 663 | 304 |
| 613 | -143 | 569 | 280 |
| 614 | -157 | 486 | 218 |
| 615 | -142 | 474 | 219 |
| 616 | -142 | 475 | 215 |
| 617 | -143 | 474 | 218 |
| 618 | -140 | 478 | 216 |
| 619 | -151 | 461 | 216 |
| 620 | -141 | 477 | 224 |
| 621 | -152 | 433 | 237 |
| 622 | -158 | 443 | 231 |
| 623 | -85 | 693 | 311 |
| 624 | -90 | 703 | 341 |
| 625 | -172 | 512 | 238 |
| 626 | -131 | 507 | 224 |
| 627 | -132 | 503 | 223 |
| 628 | -134 | 500 | 223 |
| 629 | -133 | 501 | 221 |
| 630 | -138 | 492 | 227 |
| 631 | -176 | 455 | 225 |
| 632 | -94 | 658 | 284 |
| 633 | -76 | 827 | 391 |
| 634 | -147 | 480 | 218 |
| 635 | -121 | 487 | 216 |
| 636 | -122 | 486 | 215 |
| 637 | -123 | 484 | 216 |
| 638 | -122 | 485 | 215 |
| 639 | -134 | 479 | 234 |
| 640 | -110 | 560 | 253 |
| 641 | -111 | 638 | 350 |
| 642 | -150 | 498 | 248 |
| 643 | -104 | 511 | 223 |
| 644 | -105 | 509 | 220 |
| 645 | -104 | 509 | 218 |
| 646 | -105 | 507 | 218 |
| 647 | -107 | 509 | 220 |
| 648 | -131 | 484 | 228 |
| 649 | -124 | 563 | 270 |
| 650 | -69 | 726 | 326 |
| 651 | -162 | 499 | 244 |
| 652 | -109 | 491 | 212 |
| 653 | -110 | 490 | 212 |
| 654 | -109 | 493 | 213 |
| 655 | -110 | 493 | 213 |
| 656 | -108 | 495 | 214 |
| 657 | -108 | 494 | 213 |
| 658 | -141 | 402 | 204 |
| 659 | -134 | 479 | 222 |
| 660 | -82 | 589 | 238 |
| 661 | -80 | 691 | 344 |
| 662 | -111 | 566 | 235 |
| 663 | -129 | 455 | 240 |
| 664 | -110 | 483 | 210 |
| 665 | -106 | 486 | 210 |
| 666 | -108 | 484 | 208 |
| 667 | -109 | 483 | 210 |
| 668 | -108 | 483 | 209 |
| 669 | -105 | 466 | 216 |
| 670 | -110 | 485 | 211 |
| 671 | -116 | 499 | 232 |
| 672 | -124 | 529 | 297 |
| 673 | -109 | 449 | 202 |
| 674 | -103 | 465 | 202 |
| 675 | -102 | 466 | 204 |
| 676 | -101 | 468 | 203 |
| 677 | -102 | 467 | 203 |
| 678 | -131 | 400 | 207 |
| 679 | -120 | 477 | 237 |
| 680 | -88 | 523 | 228 |
| 681 | -178 | 413 | 241 |
| 682 | -120 | 422 | 197 |
| 683 | -112 | 434 | 197 |
| 684 | -107 | 440 | 197 |
| 685 | -105 | 442 | 196 |
| 686 | -108 | 441 | 194 |
| 687 | -110 | 440 | 197 |
| 688 | -109 | 444 | 205 |
| 689 | -124 | 440 | 202 |
| 690 | -110 | 456 | 203 |
| 691 | -108 | 508 | 224 |
| 692 | -59 | 594 | 307 |
| 693 | -167 | 427 | 209 |
| 694 | -103 | 454 | 203 |
| 695 | -101 | 458 | 201 |
| 696 | -103 | 457 | 203 |
| 697 | -101 | 460 | 202 |
| 698 | -102 | 459 | 203 |
| 699 | -104 | 457 | 202 |
| 700 | -105 | 467 | 207 |
| 701 | -89 | 562 | 297 |
| 702 | -48 | 516 | 243 |
| 703 | -146 | 396 | 200 |
| 704 | -97 | 461 | 204 |
| 705 | -93 | 464 | 201 |
| 706 | -92 | 466 | 201 |
| 707 | -93 | 466 | 201 |
| 708 | -94 | 466 | 201 |
| 709 | -104 | 465 | 208 |
| 710 | -118 | 446 | 209 |
| 711 | -40 | 680 | 305 |
| 712 | -130 | 433 | 197 |
| 713 | -96 | 450 | 198 |
| 714 | -98 | 448 | 197 |
| 715 | -97 | 449 | 198 |
| 716 | -97 | 450 | 197 |
| 717 | -98 | 453 | 201 |
| 718 | -97 | 447 | 202 |
| 719 | -93 | 481 | 207 |
| 720 | -100 | 480 | 221 |
| 721 | -62 | 582 | 295 |
| 722 | -205 | 295 | 221 |
| 723 | -110 | 402 | 220 |
| 724 | -91 | 446 | 196 |
| 725 | -92 | 448 | 207 |
| 726 | -92 | 449 | 206 |
| 727 | -94 | 449 | 205 |
| 728 | -96 | 445 | 204 |
| 729 | -100 | 439 | 204 |
| 730 | -121 | 400 | 199 |
| 731 | -94 | 487 | 215 |
| 732 | -100 | 510 | 262 |
| 733 | -100 | 424 | 205 |
| 734 | -97 | 454 | 206 |
| 735 | -92 | 459 | 203 |
| 736 | -93 | 459 | 206 |
| 737 | -91 | 461 | 205 |
| 738 | -90 | 461 | 207 |
| 739 | -97 | 456 | 207 |
| 740 | -137 | 338 | 193 |
| 741 | -120 | 454 | 220 |
| 742 | -52 | 649 | 330 |
| 743 | -67 | 501 | 237 |
| 744 | -95 | 350 | 219 |
| 745 | -92 | 451 | 199 |
| 746 | -90 | 451 | 200 |
| 747 | -90 | 451 | 204 |
| 748 | -94 | 448 | 200 |
| 749 | -87 | 454 | 205 |
| 750 | -77 | 478 | 218 |
| 751 | -113 | 412 | 213 |
| 752 | -57 | 613 | 298 |
| 753 | -110 | 451 | 225 |
| 754 | -59 | 490 | 224 |
| 755 | -57 | 493 | 233 |
| 756 | -54 | 498 | 238 |
| 757 | -61 | 490 | 231 |
| 758 | -68 | 479 | 235 |
| 759 | -69 | 483 | 231 |
| 760 | -112 | 388 | 224 |
| 761 | -95 | 451 | 228 |
| 762 | -82 | 450 | 228 |
| 763 | -78 | 460 | 241 |
| 764 | -68 | 532 | 285 |
| 765 | -137 | 409 | 249 |
| 766 | -83 | 446 | 216 |
| 767 | -78 | 451 | 225 |

| | | | |
|---|---|---|---|
| 768 | -78 | 452 | 226 |
| 769 | -74 | 455 | 230 |
| 770 | -109 | 429 | 210 |
| 771 | -126 | 381 | 212 |
| 772 | -10 | 721 | 331 |
| 773 | -34 | 472 | 253 |
| 774 | -62 | 480 | 222 |
| 775 | -60 | 485 | 230 |
| 776 | -53 | 493 | 239 |
| 777 | -55 | 490 | 239 |
| 778 | -55 | 488 | 234 |
| 779 | -65 | 478 | 227 |
| 780 | -73 | 450 | 239 |
| 781 | -96 | 458 | 235 |
| 782 | -40 | 633 | 307 |
| 783 | -71 | 472 | 244 |
| 784 | -87 | 439 | 211 |
| 785 | -81 | 446 | 209 |
| 786 | -79 | 447 | 212 |
| 787 | -78 | 448 | 215 |
| 788 | -80 | 446 | 214 |
| 789 | -79 | 446 | 221 |
| 790 | -110 | 399 | 225 |
| 791 | -112 | 397 | 232 |
| 792 | -67 | 478 | 228 |
| 793 | -72 | 468 | 250 |
| 794 | -39 | 586 | 322 |
| 795 | -80 | 422 | 234 |
| 796 | -79 | 442 | 216 |
| 797 | -76 | 444 | 214 |
| 798 | -81 | 439 | 214 |
| 799 | -81 | 439 | 213 |
| 800 | -85 | 416 | 225 |
| 801 | -131 | 380 | 226 |
| 802 | -114 | 385 | 213 |
| 803 | -106 | 451 | 248 |
| 804 | -110 | 530 | 278 |
| 805 | -131 | 377 | 249 |
| 806 | -76 | 445 | 216 |
| 807 | -81 | 444 | 215 |
| 808 | -73 | 452 | 224 |
| 809 | -69 | 458 | 225 |
| 810 | -77 | 449 | 221 |
| 811 | -90 | 437 | 231 |
| 812 | -124 | 390 | 205 |
| 813 | -109 | 399 | 203 |
| 814 | -113 | 377 | 199 |
| 815 | -137 | 385 | 198 |
| 816 | -81 | 503 | 289 |
| 817 | -122 | 402 | 195 |
| 818 | -92 | 420 | 197 |
| 819 | -94 | 418 | 195 |
| 820 | -91 | 424 | 204 |
| 821 | -89 | 423 | 198 |
| 822 | -93 | 419 | 197 |
| 823 | -111 | 397 | 205 |
| 824 | -102 | 414 | 204 |
| 825 | -136 | 357 | 202 |
| 826 | -46 | 614 | 297 |
| 827 | -127 | 410 | 213 |
| 828 | -88 | 432 | 197 |
| 829 | -86 | 434 | 196 |
| 830 | -87 | 435 | 196 |
| 831 | -83 | 437 | 198 |
| 832 | -90 | 430 | 190 |
| 833 | -95 | 439 | 200 |
| 834 | -106 | 448 | 190 |
| 835 | -83 | 457 | 206 |
| 836 | -89 | 466 | 222 |
| 837 | -79 | 469 | 222 |
| 838 | -74 | 475 | 212 |
| 839 | -102 | 539 | 311 |
| 840 | -116 | 381 | 215 |
| 841 | -104 | 385 | 218 |
| 842 | -87 | 421 | 215 |
| 843 | -98 | 376 | 211 |
| 844 | -84 | 421 | 216 |
| 845 | -90 | 417 | 226 |
| 846 | -99 | 383 | 206 |
| 847 | -93 | 365 | 208 |
| 848 | -105 | 397 | 211 |
| 849 | -80 | 414 | 212 |
| 850 | -73 | 398 | 216 |
| 851 | -95 | 376 | 206 |
| 852 | -83 | 422 | 214 |
| 853 | -93 | 426 | 211 |
| 854 | -79 | 433 | 208 |
| 855 | -82 | 428 | 200 |
| 856 | -81 | 429 | 196 |
| 857 | -83 | 428 | 199 |
| 858 | -82 | 429 | 200 |
| 859 | -83 | 428 | 199 |
| 860 | -81 | 428 | 200 |
| 861 | -85 | 432 | 204 |
| 862 | -81 | 515 | 251 |
| 863 | -112 | 365 | 207 |
| 864 | -88 | 429 | 200 |
| 865 | -84 | 432 | 198 |
| 866 | -85 | 432 | 197 |
| 867 | -97 | 386 | 196 |
| 868 | -89 | 431 | 200 |

| | | | |
|---|---|---|---|
| 869 | -64 | 545 | 243 |
| 870 | -52 | 599 | 256 |
| 871 | -41 | 587 | 253 |
| 872 | -122 | 446 | 226 |
| 873 | -68 | 457 | 222 |
| 874 | -65 | 458 | 219 |
| 875 | -68 | 455 | 219 |
| 876 | -67 | 453 | 217 |
| 877 | -67 | 455 | 216 |
| 878 | -110 | 400 | 215 |
| 879 | -101 | 394 | 203 |
| 880 | -68 | 482 | 252 |
| 881 | -60 | 499 | 253 |
| 882 | -72 | 447 | 212 |
| 883 | -65 | 448 | 223 |
| 884 | -64 | 455 | 224 |
| 885 | -63 | 456 | 232 |
| 886 | -65 | 455 | 234 |
| 887 | -62 | 457 | 229 |
| 888 | -67 | 451 | 222 |
| 889 | -70 | 448 | 216 |
| 890 | -74 | 445 | 224 |
| 891 | -72 | 474 | 231 |
| 892 | -37 | 526 | 244 |
| 893 | -76 | 483 | 255 |
| 894 | -61 | 462 | 226 |
| 895 | -58 | 465 | 224 |
| 896 | -60 | 463 | 224 |
| 897 | -58 | 464 | 225 |
| 898 | -60 | 462 | 224 |
| 899 | -59 | 462 | 222 |
| 900 | -73 | 452 | 231 |
| 901 | -91 | 419 | 211 |
| 902 | -122 | 510 | 308 |
| 903 | -115 | 376 | 236 |
| 904 | -73 | 451 | 224 |
| 905 | -74 | 438 | 218 |
| 906 | -73 | 439 | 218 |
| 907 | -75 | 437 | 212 |
| 908 | -72 | 440 | 214 |
| 909 | -71 | 440 | 212 |
| 910 | -72 | 438 | 212 |
| 911 | -72 | 439 | 215 |
| 912 | -108 | 364 | 212 |
| 913 | -75 | 440 | 235 |
| 914 | -31 | 572 | 283 |
| 915 | -97 | 496 | 305 |
| 916 | -79 | 413 | 217 |
| 917 | -71 | 433 | 215 |
| 918 | -69 | 436 | 213 |
| 919 | -68 | 437 | 212 |
| 920 | -68 | 438 | 215 |
| 921 | -68 | 436 | 215 |
| 922 | -136 | 274 | 174 |
| 923 | -128 | 390 | 220 |
| 924 | -91 | 461 | 247 |
| 925 | -71 | 501 | 269 |
| 926 | -45 | 583 | 270 |
| 927 | -61 | 465 | 228 |
| 928 | -60 | 464 | 220 |
| 929 | -59 | 469 | 235 |
| 930 | -56 | 470 | 232 |
| 931 | -64 | 459 | 222 |
| 932 | -64 | 460 | 214 |
| 933 | -66 | 457 | 211 |
| 934 | -72 | 456 | 216 |
| 935 | -67 | 455 | 211 |
| 936 | -33 | 588 | 259 |
| 937 | -50 | 596 | 285 |
| 938 | -95 | 455 | 233 |
| 939 | -65 | 454 | 216 |
| 940 | -59 | 460 | 216 |
| 941 | -58 | 462 | 217 |
| 942 | -56 | 463 | 215 |
| 943 | -56 | 463 | 216 |
| 944 | -55 | 464 | 216 |
| 945 | -56 | 463 | 217 |
| 946 | -57 | 463 | 214 |
| 947 | -55 | 464 | 217 |
| 948 | -56 | 463 | 220 |
| 949 | -73 | 431 | 215 |
| 950 | -76 | 469 | 236 |
| 951 | -88 | 380 | 204 |
| 952 | -64 | 447 | 212 |
| 953 | -64 | 449 | 212 |
| 954 | -63 | 451 | 213 |
| 955 | -65 | 449 | 211 |
| 956 | -68 | 453 | 217 |
| 957 | -129 | 342 | 208 |
| 958 | -60 | 543 | 286 |
| 959 | -79 | 554 | 263 |
| 960 | -94 | 404 | 240 |
| 961 | -57 | 461 | 212 |
| 962 | -57 | 461 | 213 |
| 963 | -57 | 461 | 210 |
| 964 | -56 | 462 | 212 |
| 965 | -94 | 351 | 196 |
| 966 | -79 | 409 | 214 |
| 967 | -95 | 445 | 277 |
| 968 | -58 | 614 | 269 |
| 969 | -107 | 430 | 210 |

| | | | |
|---|---|---|---|
| 970 | -64 | 437 | 215 |
| 971 | -65 | 435 | 218 |
| 972 | -65 | 439 | 220 |
| 973 | -67 | 435 | 219 |
| 974 | -75 | 428 | 212 |
| 975 | -97 | 426 | 227 |
| 976 | -124 | 400 | 229 |
| 977 | -124 | 466 | 314 |
| 978 | -52 | 500 | 259 |
| 979 | -52 | 482 | 248 |
| 980 | -59 | 451 | 220 |
| 981 | -60 | 450 | 220 |
| 982 | -57 | 453 | 229 |
| 983 | -59 | 451 | 218 |
| 984 | -61 | 449 | 218 |
| 985 | -83 | 412 | 224 |
| 986 | -82 | 427 | 215 |
| 987 | -91 | 456 | 251 |
| 988 | -67 | 539 | 276 |
| 989 | -70 | 445 | 222 |
| 990 | -68 | 443 | 219 |
| 991 | -68 | 442 | 220 |
| 992 | -67 | 442 | 216 |
| 993 | -88 | 425 | 228 |
| 994 | -109 | 368 | 210 |
| 995 | -101 | 362 | 206 |
| 996 | -71 | 397 | 214 |
| 997 | -75 | 403 | 209 |
| 998 | -89 | 397 | 213 |
| 999 | -80 | 430 | 247 |
| 1000 | -76 | 560 | 278 |
| 1001 | -64 | 391 | 217 |
| 1002 | -68 | 430 | 221 |
| 1003 | -60 | 443 | 221 |
| 1004 | -102 | 346 | 205 |
| 1005 | -94 | 410 | 239 |
| 1006 | -83 | 427 | 229 |
| 1007 | -77 | 482 | 243 |
| 1008 | -73 | 537 | 255 |
| 1009 | -87 | 449 | 225 |
| 1010 | -74 | 436 | 226 |
| 1011 | -72 | 435 | 225 |
| 1012 | -73 | 433 | 223 |
| 1013 | -71 | 436 | 224 |
| 1014 | -72 | 435 | 227 |
| 1015 | -71 | 434 | 230 |
| 1016 | -79 | 439 | 243 |
| 1017 | -79 | 335 | 200 |
| 1018 | -82 | 379 | 223 |
| 1019 | -56 | 537 | 279 |
| 1020 | -61 | 457 | 229 |
| 1021 | -59 | 445 | 219 |
| 1022 | -60 | 444 | 220 |
| 1023 | -63 | 438 | 217 |
| 1024 | -57 | 446 | 226 |
| 1025 | -54 | 451 | 233 |
| 1026 | -55 | 449 | 233 |
| 1027 | -61 | 454 | 237 |
| 1028 | -55 | 449 | 236 |
| 1029 | -39 | 421 | 207 |
| 1030 | -71 | 445 | 256 |
| 1031 | -13 | 620 | 295 |
| 1032 | -24 | 597 | 286 |
| 1033 | -81 | 429 | 245 |
| 1034 | -56 | 455 | 243 |
| 1035 | -54 | 457 | 241 |
| 1036 | -55 | 455 | 240 |
| 1037 | -55 | 455 | 241 |
| 1038 | -61 | 450 | 246 |
| 1039 | -94 | 355 | 229 |
| 1040 | -44 | 479 | 261 |
| 1041 | -72 | 452 | 270 |
| 1042 | -89 | 395 | 255 |
| 1043 | -82 | 394 | 249 |
| 1044 | -83 | 402 | 247 |
| 1045 | -79 | 407 | 256 |
| 1046 | -89 | 520 | 288 |
| 1047 | -70 | 417 | 246 |
| 1048 | -65 | 413 | 236 |
| 1049 | -64 | 414 | 237 |
| 1050 | -63 | 416 | 237 |
| 1051 | -63 | 415 | 238 |
| 1052 | -84 | 352 | 214 |
| 1053 | -70 | 442 | 263 |
| 1054 | -61 | 457 | 265 |
| 1055 | -62 | 431 | 242 |
| 1056 | -62 | 430 | 243 |
| 1057 | -61 | 429 | 241 |
| 1058 | -61 | 428 | 240 |
| 1059 | -62 | 426 | 241 |
| 1060 | -87 | 310 | 217 |
| 1061 | -43 | 533 | 272 |
| 1062 | -36 | 486 | 248 |
| 1063 | -53 | 452 | 245 |
| 1064 | -51 | 453 | 244 |
| 1065 | -50 | 452 | 243 |
| 1066 | -49 | 452 | 244 |
| 1067 | -51 | 448 | 238 |
| 1068 | -50 | 446 | 238 |
| 1069 | -50 | 445 | 240 |

## 9.3 *Complete Raw Data for Cadaver 2*

### *9.3.1 Mid-Palatal Suture Sensor*

| time | 1 | 2 | 3 |
|---|---|---|---|
| 1 | -1 | -2 | 2 |
| 2 | -1 | -1 | 3 |
| 3 | -6 | 0 | 8 |
| 4 | -1 | -1 | 4 |
| 5 | 0 | 1 | 4 |
| 6 | -4 | 0 | 5 |
| 7 | -8 | 2 | 4 |
| 8 | -3 | 2 | 6 |
| 9 | -2 | 0 | 7 |
| 10 | -1 | -1 | 8 |
| 11 | 2 | -2 | 10 |
| 12 | 0 | -1 | 11 |
| 13 | -3 | 4 | 8 |
| 14 | -7 | 5 | 8 |
| 15 | -17 | 6 | 10 |
| 16 | -3 | 4 | 10 |
| 17 | -2 | 4 | 10 |
| 18 | 1 | 5 | 10 |
| 19 | 0 | 4 | 10 |
| 20 | 1 | 6 | 11 |
| 21 | -2 | 6 | 11 |
| 22 | -3 | 8 | 11 |
| 23 | -4 | 7 | 13 |
| 24 | -6 | 8 | 13 |
| 25 | -5 | 8 | 14 |
| 26 | -4 | 7 | 14 |
| 27 | -2 | 8 | 15 |
| 28 | 3 | 7 | 16 |
| 29 | 2 | 8 | 16 |
| 30 | -9 | 12 | 12 |
| 31 | -3 | 10 | 17 |
| 32 | -1 | 10 | 17 |
| 33 | -5 | 13 | 16 |
| 34 | -2 | 14 | 15 |
| 35 | -1 | 8 | 19 |
| 36 | 3 | 5 | 21 |
| 37 | 1 | 10 | 18 |
| 38 | 2 | 12 | 18 |
| 39 | -4 | 13 | 19 |
| 40 | 2 | 11 | 21 |
| 41 | 1 | 13 | 21 |
| 42 | 0 | 11 | 22 |
| 43 | 1 | 13 | 23 |
| 44 | 1 | 12 | 23 |
| 45 | 1 | 12 | 23 |
| 46 | 0 | 13 | 23 |
| 47 | -2 | 15 | 23 |
| 48 | -3 | 14 | 23 |
| 49 | -2 | 16 | 22 |
| 50 | -1 | 15 | 23 |
| 51 | -9 | 18 | 23 |
| 52 | -1 | 15 | 25 |
| 53 | -1 | 16 | 24 |
| 54 | -2 | 17 | 25 |
| 55 | 0 | 18 | 24 |
| 56 | 0 | 17 | 24 |
| 57 | 3 | 15 | 27 |
| 58 | 1 | 16 | 27 |
| 59 | 1 | 17 | 27 |
| 60 | -3 | 19 | 27 |
| 61 | -1 | 24 | 22 |
| 62 | -1 | 19 | 28 |
| 63 | 0 | 18 | 28 |
| 64 | 0 | 18 | 28 |
| 65 | 1 | 20 | 27 |
| 66 | 0 | 19 | 28 |
| 67 | -6 | 18 | 29 |
| 68 | -2 | 20 | 30 |
| 69 | -3 | 21 | 30 |
| 70 | -3 | 22 | 29 |
| 71 | 14 | 14 | 32 |
| 72 | -4 | 22 | 30 |
| 73 | 0 | 21 | 32 |
| 74 | -1 | 21 | 32 |
| 75 | -3 | 16 | 32 |
| 76 | -3 | 23 | 32 |
| 77 | -4 | 23 | 32 |
| 78 | -2 | 21 | 33 |
| 79 | -15 | 24 | 34 |
| 80 | -9 | 27 | 32 |
| 81 | -7 | 24 | 32 |
| 82 | -7 | 21 | 36 |
| 83 | -1 | 23 | 35 |
| 84 | -5 | 26 | 35 |
| 85 | -15 | 29 | 34 |
| 86 | -5 | 25 | 36 |
| 87 | -5 | 25 | 36 |
| 88 | -4 | 25 | 37 |
| 89 | -4 | 25 | 37 |
| 90 | -5 | 25 | 37 |
| 91 | -3 | 24 | 39 |
| 92 | -4 | 24 | 38 |
| 93 | -5 | 26 | 39 |
| 94 | 1 | 26 | 40 |
| 95 | -3 | 26 | 39 |
| 96 | 11 | 28 | 41 |
| 97 | -2 | 26 | 40 |
| 98 | -8 | 27 | 41 |
| 99 | 3 | 25 | 41 |
| 100 | 4 | 25 | 41 |
| 101 | 5 | 25 | 42 |
| 102 | 5 | 25 | 42 |
| 103 | 3 | 26 | 42 |
| 104 | 8 | 26 | 42 |
| 105 | 9 | 25 | 43 |
| 106 | 2 | 28 | 41 |
| 107 | -2 | 34 | 37 |
| 108 | 3 | 30 | 43 |
| 109 | 7 | 27 | 44 |
| 110 | 9 | 30 | 45 |
| 111 | 6 | 33 | 46 |
| 112 | 9 | 28 | 44 |
| 113 | 8 | 28 | 44 |
| 114 | 5 | 28 | 42 |
| 115 | -7 | 33 | 43 |
| 116 | 3 | 30 | 43 |
| 117 | 3 | 31 | 43 |
| 118 | 4 | 30 | 44 |
| 119 | 4 | 30 | 42 |
| 120 | 6 | 29 | 45 |
| 121 | 10 | 29 | 45 |
| 122 | 5 | 30 | 46 |
| 123 | 8 | 29 | 45 |
| 124 | 0 | 32 | 44 |
| 125 | -1 | 32 | 45 |
| 126 | -5 | 35 | 41 |
| 127 | 18 | 26 | 42 |
| 128 | -4 | 28 | 44 |
| 129 | 11 | 31 | 41 |
| 130 | 3 | 31 | 47 |
| 131 | -2 | 34 | 46 |
| 132 | 0 | 32 | 47 |
| 133 | -14 | 40 | 41 |
| 134 | 13 | 26 | 50 |
| 135 | 5 | 33 | 48 |
| 136 | 5 | 33 | 48 |
| 137 | 7 | 33 | 47 |
| 138 | 0 | 34 | 44 |
| 139 | -1 | 33 | 49 |
| 140 | -4 | 39 | 44 |
| 141 | -23 | 52 | 37 |
| 142 | 4 | 35 | 49 |
| 143 | 6 | 34 | 49 |
| 144 | 9 | 32 | 52 |
| 145 | -2 | 41 | 36 |
| 146 | 6 | 36 | 50 |
| 147 | 7 | 36 | 50 |
| 148 | 5 | 36 | 51 |
| 149 | -1 | 49 | 37 |
| 150 | 8 | 36 | 52 |
| 151 | 8 | 36 | 52 |
| 152 | 8 | 37 | 52 |
| 153 | 4 | 39 | 52 |
| 154 | -1 | 40 | 52 |
| 155 | 3 | 39 | 52 |
| 156 | 6 | 43 | 49 |
| 157 | 5 | 41 | 52 |
| 158 | 8 | 38 | 54 |
| 159 | 9 | 38 | 54 |
| 160 | 11 | 37 | 55 |
| 161 | 5 | 41 | 54 |
| 162 | 6 | 40 | 55 |
| 163 | 4 | 40 | 52 |
| 164 | 8 | 40 | 56 |
| 165 | 6 | 44 | 51 |
| 166 | 8 | 41 | 56 |
| 167 | 11 | 40 | 57 |
| 168 | 11 | 40 | 57 |
| 169 | 9 | 42 | 55 |
| 170 | 5 | 43 | 55 |
| 171 | -1 | 45 | 57 |
| 172 | 5 | 42 | 58 |
| 173 | 5 | 45 | 55 |
| 174 | 4 | 45 | 57 |
| 175 | 0 | 48 | 52 |
| 176 | 3 | 44 | 46 |
| 177 | 8 | 41 | 59 |
| 178 | 4 | 49 | 58 |
| 179 | 5 | 45 | 59 |
| 180 | -7 | 52 | 54 |
| 181 | 10 | 45 | 60 |
| 182 | 11 | 44 | 60 |
| 183 | 12 | 45 | 60 |
| 184 | 7 | 47 | 60 |
| 185 | 9 | 46 | 60 |
| 186 | 11 | 45 | 61 |
| 187 | 11 | 45 | 61 |
| 188 | 7 | 47 | 60 |
| 189 | 9 | 47 | 61 |
| 190 | 9 | 47 | 62 |
| 191 | 12 | 46 | 62 |
| 192 | 12 | 47 | 62 |
| 193 | 13 | 47 | 62 |
| 194 | 8 | 49 | 62 |
| 195 | 8 | 48 | 62 |
| 196 | 10 | 49 | 63 |
| 197 | 12 | 48 | 64 |
| 198 | 12 | 49 | 61 |
| 199 | 13 | 47 | 65 |
| 200 | 12 | 48 | 65 |
| 201 | 14 | 48 | 65 |
| 202 | 14 | 48 | 65 |
| 203 | 15 | 49 | 66 |
| 204 | 16 | 49 | 67 |
| 205 | 15 | 49 | 66 |
| 206 | 13 | 51 | 66 |
| 207 | 11 | 51 | 67 |
| 208 | 2 | 56 | 67 |
| 209 | 9 | 54 | 65 |
| 210 | -8 | 59 | 64 |
| 211 | 17 | 52 | 68 |
| 212 | 14 | 51 | 68 |
| 213 | 14 | 52 | 69 |
| 214 | 12 | 52 | 69 |
| 215 | 12 | 54 | 68 |
| 216 | 11 | 54 | 69 |
| 217 | 8 | 56 | 68 |
| 218 | 0 | 63 | 58 |
| 219 | 13 | 53 | 70 |
| 220 | 15 | 53 | 70 |
| 221 | 16 | 53 | 71 |
| 222 | 15 | 54 | 69 |
| 223 | 2 | 59 | 68 |
| 224 | 6 | 59 | 67 |
| 225 | 12 | 54 | 71 |
| 226 | 13 | 56 | 71 |
| 227 | 13 | 56 | 71 |
| 228 | 12 | 58 | 71 |
| 229 | 9 | 59 | 71 |
| 230 | 13 | 56 | 71 |
| 231 | 12 | 59 | 71 |
| 232 | 12 | 59 | 72 |
| 233 | 13 | 58 | 72 |
| 234 | 14 | 58 | 73 |
| 235 | 19 | 56 | 75 |
| 236 | 20 | 56 | 74 |
| 237 | 15 | 58 | 74 |
| 238 | 10 | 60 | 73 |
| 239 | 9 | 60 | 74 |
| 240 | 10 | 61 | 71 |
| 241 | 13 | 60 | 74 |
| 242 | 15 | 59 | 75 |
| 243 | 15 | 59 | 75 |
| 244 | 16 | 60 | 76 |
| 245 | 9 | 64 | 74 |
| 246 | 12 | 62 | 75 |
| 247 | 9 | 63 | 74 |
| 248 | 6 | 66 | 75 |
| 249 | 10 | 63 | 74 |
| 250 | -6 | 67 | 73 |
| 251 | 17 | 64 | 75 |
| 252 | 16 | 62 | 76 |
| 253 | 17 | 59 | 77 |
| 254 | 20 | 58 | 77 |
| 255 | 19 | 66 | 77 |
| 256 | 19 | 62 | 78 |
| 257 | 19 | 62 | 78 |
| 258 | 10 | 65 | 77 |
| 259 | 12 | 65 | 77 |
| 260 | 11 | 66 | 77 |
| 261 | 5 | 69 | 76 |
| 262 | 5 | 68 | 78 |
| 263 | -3 | 71 | 76 |
| 264 | 21 | 62 | 79 |
| 265 | 19 | 63 | 79 |
| 266 | 21 | 64 | 80 |
| 267 | 21 | 65 | 79 |
| 268 | 17 | 66 | 79 |
| 269 | 14 | 70 | 76 |
| 270 | 4 | 70 | 79 |
| 271 | -10 | 74 | 78 |
| 272 | 23 | 69 | 80 |
| 273 | 20 | 65 | 82 |
| 274 | 22 | 65 | 82 |
| 275 | 18 | 66 | 82 |
| 276 | 17 | 67 | 82 |
| 277 | 18 | 65 | 82 |
| 278 | -6 | 77 | 81 |
| 279 | 19 | 66 | 83 |
| 280 | 22 | 66 | 83 |
| 281 | 23 | 66 | 83 |
| 282 | 18 | 68 | 83 |
| 283 | 20 | 68 | 84 |
| 284 | 17 | 68 | 83 |
| 285 | 16 | 68 | 84 |
| 286 | 8 | 68 | 83 |
| 287 | 13 | 71 | 83 |
| 288 | 31 | 60 | 89 |
| 289 | 34 | 61 | 85 |
| 290 | 25 | 67 | 86 |
| 291 | 20 | 66 | 85 |
| 292 | 26 | 79 | 87 |
| 293 | 15 | 69 | 85 |
| 294 | 12 | 70 | 86 |
| 295 | 21 | 69 | 87 |
| 296 | 23 | 70 | 88 |
| 297 | 27 | 69 | 88 |
| 298 | 21 | 68 | 90 |
| 299 | 24 | 70 | 89 |
| 300 | 24 | 70 | 90 |
| 301 | 27 | 67 | 92 |
| 302 | 20 | 72 | 89 |
| 303 | 18 | 68 | 94 |
| 304 | 25 | 70 | 94 |
| 305 | 30 | 68 | 94 |
| 306 | 34 | 69 | 93 |
| 307 | 25 | 71 | 93 |
| 308 | 25 | 74 | 92 |

| | | | |
|---|---|---|---|
| 309 | 24 | 75 | 93 |
| 310 | 30 | 71 | 93 |
| 311 | 26 | 74 | 93 |
| 312 | 24 | 75 | 93 |
| 313 | 17 | 77 | 95 |
| 314 | 10 | 80 | 89 |
| 315 | 25 | 73 | 94 |
| 316 | 28 | 73 | 95 |
| 317 | 29 | 74 | 95 |
| 318 | 29 | 74 | 95 |
| 319 | 30 | 75 | 95 |
| 320 | 28 | 75 | 96 |
| 321 | 22 | 77 | 95 |
| 322 | 26 | 77 | 96 |
| 323 | 28 | 75 | 97 |
| 324 | 31 | 74 | 97 |
| 325 | 30 | 78 | 96 |
| 326 | 28 | 76 | 97 |
| 327 | 28 | 77 | 97 |
| 328 | 31 | 75 | 97 |
| 329 | 13 | 89 | 93 |
| 330 | 14 | 77 | 94 |
| 331 | 28 | 76 | 98 |
| 332 | 38 | 72 | 99 |
| 333 | 40 | 72 | 100 |
| 334 | 41 | 72 | 101 |
| 335 | 29 | 73 | 101 |
| 336 | 29 | 76 | 99 |
| 337 | 30 | 70 | 99 |
| 338 | 29 | 75 | 102 |
| 339 | 26 | 76 | 101 |
| 340 | 29 | 75 | 103 |
| 341 | 22 | 76 | 104 |
| 342 | 22 | 77 | 101 |
| 343 | 28 | 77 | 101 |
| 344 | 23 | 81 | 96 |
| 345 | 35 | 74 | 103 |
| 346 | 25 | 81 | 96 |
| 347 | 36 | 74 | 103 |
| 348 | 39 | 73 | 104 |
| 349 | 39 | 73 | 104 |
| 350 | 40 | 73 | 104 |
| 351 | 40 | 73 | 104 |
| 352 | 35 | 76 | 104 |
| 353 | 30 | 76 | 105 |
| 354 | 29 | 76 | 103 |
| 355 | 37 | 76 | 105 |
| 356 | 35 | 76 | 106 |
| 357 | 34 | 77 | 106 |
| 358 | 36 | 76 | 106 |
| 359 | 37 | 75 | 106 |
| 360 | 40 | 75 | 106 |
| 361 | 41 | 75 | 107 |
| 362 | 39 | 78 | 106 |
| 363 | 39 | 76 | 107 |
| 364 | 30 | 79 | 106 |
| 365 | 37 | 80 | 106 |
| 366 | 31 | 82 | 104 |
| 367 | 14 | 83 | 106 |
| 368 | 38 | 77 | 107 |
| 369 | 40 | 76 | 108 |
| 370 | 42 | 76 | 108 |
| 371 | 43 | 76 | 108 |
| 372 | 39 | 79 | 108 |
| 373 | 34 | 79 | 107 |
| 374 | 35 | 80 | 107 |

| | | | |
|---|---|---|---|
| 375 | 35 | 81 | 107 |
| 376 | 37 | 80 | 108 |
| 377 | 45 | 77 | 109 |
| 378 | 36 | 80 | 108 |
| 379 | 31 | 81 | 110 |
| 380 | 43 | 79 | 109 |
| 381 | 36 | 82 | 109 |
| 382 | 16 | 89 | 109 |
| 383 | 23 | 85 | 107 |
| 384 | 17 | 88 | 106 |
| 385 | 24 | 86 | 108 |
| 386 | 14 | 92 | 106 |
| 387 | 19 | 89 | 108 |
| 388 | 27 | 85 | 110 |
| 389 | 16 | 86 | 111 |
| 390 | 32 | 85 | 110 |
| 391 | 34 | 84 | 111 |
| 392 | 39 | 82 | 112 |
| 393 | 40 | 81 | 112 |
| 394 | 40 | 83 | 112 |
| 395 | 40 | 82 | 113 |
| 396 | 39 | 83 | 112 |
| 397 | 39 | 83 | 113 |
| 398 | 40 | 83 | 113 |
| 399 | 40 | 83 | 114 |
| 400 | 42 | 83 | 115 |
| 401 | 41 | 83 | 114 |
| 402 | 42 | 83 | 115 |
| 403 | 46 | 83 | 114 |
| 404 | 42 | 84 | 115 |
| 405 | 39 | 88 | 115 |
| 406 | 27 | 93 | 110 |
| 407 | 40 | 90 | 114 |
| 408 | 24 | 90 | 115 |
| 409 | 41 | 86 | 116 |
| 410 | 42 | 85 | 116 |
| 411 | 44 | 85 | 117 |
| 412 | 52 | 84 | 117 |
| 413 | 38 | 90 | 111 |
| 414 | 41 | 87 | 116 |
| 415 | 43 | 86 | 117 |
| 416 | 44 | 86 | 116 |
| 417 | 38 | 89 | 116 |
| 418 | 36 | 89 | 115 |
| 419 | 28 | 92 | 115 |
| 420 | 41 | 89 | 116 |
| 421 | 44 | 88 | 117 |
| 422 | 46 | 88 | 118 |
| 423 | 46 | 88 | 118 |
| 424 | 46 | 88 | 118 |
| 425 | 35 | 93 | 116 |
| 426 | 43 | 90 | 117 |
| 427 | 41 | 90 | 118 |
| 428 | 40 | 92 | 118 |
| 429 | 39 | 91 | 119 |
| 430 | 44 | 91 | 117 |
| 431 | 43 | 89 | 122 |
| 432 | 44 | 88 | 120 |
| 433 | 48 | 89 | 121 |
| 434 | 45 | 88 | 122 |
| 435 | 47 | 88 | 122 |
| 436 | 49 | 87 | 122 |
| 437 | 40 | 89 | 122 |
| 438 | 42 | 89 | 121 |
| 439 | 51 | 87 | 122 |
| 440 | 47 | 87 | 123 |

| | | | |
|---|---|---|---|
| 441 | 36 | 94 | 119 |
| 442 | 41 | 91 | 122 |
| 443 | 38 | 97 | 118 |
| 444 | 43 | 90 | 123 |
| 445 | 46 | 92 | 121 |
| 446 | 45 | 88 | 119 |
| 447 | 27 | 99 | 119 |
| 448 | 43 | 91 | 122 |
| 449 | 41 | 91 | 123 |
| 450 | 43 | 91 | 123 |
| 451 | 39 | 92 | 123 |
| 452 | 40 | 92 | 122 |
| 453 | 40 | 92 | 122 |
| 454 | 40 | 92 | 122 |
| 455 | 41 | 91 | 122 |
| 456 | 40 | 92 | 122 |
| 457 | 43 | 90 | 121 |
| 458 | 37 | 92 | 121 |
| 459 | 28 | 93 | 123 |
| 460 | 18 | 94 | 123 |
| 461 | 33 | 94 | 121 |
| 462 | 38 | 93 | 122 |
| 463 | 39 | 93 | 122 |
| 464 | 39 | 93 | 122 |
| 465 | 38 | 94 | 122 |
| 466 | 39 | 94 | 122 |
| 467 | 30 | 96 | 121 |
| 468 | 26 | 102 | 117 |
| 469 | 35 | 95 | 121 |
| 470 | 39 | 94 | 121 |
| 471 | 40 | 94 | 122 |
| 472 | 40 | 94 | 122 |
| 473 | 38 | 95 | 121 |
| 474 | 40 | 94 | 122 |
| 475 | 41 | 94 | 126 |
| 476 | 41 | 94 | 122 |
| 477 | 42 | 93 | 123 |
| 478 | 42 | 94 | 122 |
| 479 | 40 | 93 | 124 |
| 480 | 45 | 92 | 125 |
| 481 | 42 | 94 | 125 |
| 482 | 32 | 98 | 123 |
| 483 | 34 | 99 | 120 |
| 484 | 40 | 94 | 123 |
| 485 | 41 | 95 | 123 |
| 486 | 41 | 95 | 123 |
| 487 | 42 | 94 | 123 |
| 488 | 40 | 95 | 123 |
| 489 | 40 | 95 | 123 |
| 490 | 40 | 95 | 123 |
| 491 | 40 | 96 | 124 |
| 492 | 40 | 95 | 123 |
| 493 | 40 | 96 | 123 |
| 494 | 42 | 95 | 124 |
| 495 | 42 | 95 | 124 |
| 496 | 37 | 96 | 123 |
| 497 | 33 | 98 | 124 |
| 498 | 31 | 101 | 121 |
| 499 | 27 | 104 | 119 |
| 500 | 28 | 96 | 123 |
| 501 | 39 | 97 | 124 |
| 502 | 40 | 97 | 125 |
| 503 | 44 | 90 | 126 |
| 504 | 47 | 93 | 126 |

## *9.3.2 Intermaxillary Suture Sensor*

| time | 1 | 2 | 3 |
|---|---|---|---|
| 1 | -3 | 5 | -1 |
| 2 | -3 | 5 | -1 |
| 3 | -6 | 11 | 3 |
| 4 | -4 | 8 | -7 |
| 5 | -7 | 14 | -4 |
| 6 | -7 | 15 | -5 |
| 7 | -7 | 15 | -5 |
| 8 | -7 | 15 | -5 |
| 9 | -7 | 16 | -4 |
| 10 | -6 | 15 | -4 |
| 11 | -7 | 15 | -4 |
| 12 | -5 | 15 | -7 |
| 13 | -8 | 16 | -6 |
| 14 | -8 | 19 | -6 |
| 15 | -8 | 18 | -6 |
| 16 | -8 | 17 | -5 |
| 17 | -6 | 14 | -4 |
| 18 | -7 | 16 | -3 |
| 19 | -7 | 16 | -2 |
| 20 | -6 | 13 | -7 |
| 21 | -8 | 17 | -5 |
| 22 | -8 | 17 | -5 |
| 23 | -8 | 17 | -5 |
| 24 | -8 | 18 | -4 |
| 25 | -7 | 16 | -5 |
| 26 | -6 | 16 | -5 |
| 27 | -8 | 16 | -3 |
| 28 | -6 | 15 | 0 |
| 29 | -7 | 16 | -5 |
| 30 | -8 | 17 | -5 |
| 31 | -8 | 17 | -5 |
| 32 | -8 | 17 | -4 |
| 33 | -7 | 17 | -4 |
| 34 | -7 | 18 | -4 |
| 35 | -6 | 17 | -1 |
| 36 | -7 | 20 | 5 |

| | | | |
|---|---|---|---|
| 37 | -4 | 11 | 2 |
| 38 | -1 | 14 | 2 |
| 39 | -6 | 14 | 3 |
| 40 | -4 | 15 | 4 |
| 41 | -5 | 20 | -2 |
| 42 | -6 | 14 | -3 |
| 43 | -7 | 18 | -3 |
| 44 | -6 | 18 | -4 |
| 45 | -6 | 18 | -4 |
| 46 | -6 | 18 | -3 |
| 47 | -1 | 13 | 1 |
| 48 | -5 | 16 | -2 |
| 49 | -6 | 19 | 0 |
| 50 | 3 | 13 | 6 |
| 51 | -2 | 16 | 1 |
| 52 | -1 | 13 | 2 |
| 53 | -1 | 16 | -1 |
| 54 | -3 | 17 | -3 |
| 55 | -4 | 15 | -2 |
| 56 | -5 | 20 | -2 |
| 57 | -4 | 20 | -2 |
| 58 | -4 | 20 | -2 |
| 59 | 0 | 14 | 4 |
| 60 | 1 | 14 | 3 |
| 61 | 4 | 12 | 4 |
| 62 | 3 | 14 | 2 |
| 63 | 8 | 10 | 6 |
| 64 | 5 | 12 | 8 |
| 65 | 0 | 19 | 7 |
| 66 | 2 | 17 | 2 |
| 67 | 2 | 14 | 1 |
| 68 | 3 | 15 | -1 |
| 69 | 2 | 15 | -4 |
| 70 | 1 | 19 | 3 |
| 71 | 3 | 18 | 4 |
| 72 | 0 | 20 | 2 |
| 73 | 0 | 21 | 1 |

| | | | |
|---|---|---|---|
| 74 | 3 | 23 | 10 |
| 75 | -3 | 23 | 1 |
| 76 | -3 | 20 | 5 |
| 77 | 0 | 21 | 6 |
| 78 | -1 | 20 | 8 |
| 79 | -2 | 19 | 5 |
| 80 | -2 | 21 | 7 |
| 81 | 1 | 21 | 7 |
| 82 | 1 | 21 | 9 |
| 83 | 5 | 18 | 4 |
| 84 | -1 | 24 | 7 |
| 85 | -2 | 24 | 7 |
| 86 | -2 | 24 | 7 |
| 87 | -1 | 25 | 9 |
| 88 | -2 | 24 | 10 |
| 89 | -1 | 24 | 9 |
| 90 | 0 | 26 | 2 |
| 91 | -4 | 26 | 7 |
| 92 | -3 | 26 | 7 |
| 93 | -3 | 26 | 7 |
| 94 | -3 | 26 | 7 |
| 95 | -2 | 25 | 7 |
| 96 | -1 | 25 | 9 |
| 97 | 0 | 25 | 10 |
| 98 | 1 | 23 | 7 |
| 99 | -3 | 26 | 7 |
| 100 | -2 | 26 | 8 |
| 101 | 0 | 24 | 8 |
| 102 | -4 | 26 | 5 |
| 103 | -4 | 26 | 8 |
| 104 | -2 | 26 | 8 |
| 105 | 0 | 28 | 13 |
| 106 | -2 | 26 | 9 |
| 107 | 1 | 23 | 8 |
| 108 | 1 | 25 | 3 |
| 109 | 0 | 22 | 9 |
| 110 | -6 | 28 | -1 |

| | | | |
|---|---|---|---|
| 111 | 2 | 28 | 0 |
| 112 | -5 | 32 | -2 |
| 113 | -4 | 30 | 5 |
| 114 | -3 | 30 | 5 |
| 115 | -3 | 29 | 6 |
| 116 | -2 | 28 | 8 |
| 117 | -1 | 29 | 8 |
| 118 | 3 | 23 | 7 |
| 119 | 0 | 28 | 8 |
| 120 | -1 | 30 | 8 |
| 121 | -1 | 30 | 8 |
| 122 | -1 | 30 | 8 |
| 123 | -1 | 30 | 8 |
| 124 | -1 | 31 | 8 |
| 125 | -1 | 32 | 7 |
| 126 | -2 | 32 | 4 |
| 127 | -2 | 32 | 6 |
| 128 | -1 | 32 | 8 |
| 129 | -1 | 32 | 9 |
| 130 | -3 | 33 | 8 |
| 131 | 0 | 31 | 10 |
| 132 | 0 | 33 | 11 |
| 133 | -2 | 35 | 4 |
| 134 | -7 | 42 | -6 |
| 135 | -14 | 44 | -6 |
| 136 | -8 | 39 | 3 |
| 137 | -6 | 37 | 4 |
| 138 | -5 | 30 | 5 |
| 139 | -5 | 39 | 4 |
| 140 | -5 | 38 | 4 |
| 141 | -4 | 38 | 2 |
| 142 | -9 | 42 | -6 |
| 143 | -22 | 50 | -12 |
| 144 | -12 | 44 | -2 |
| 145 | -10 | 43 | -1 |
| 146 | -10 | 44 | -1 |
| 147 | -8 | 41 | 2 |
| 148 | -10 | 42 | -2 |
| 149 | -16 | 51 | -15 |
| 150 | -20 | 53 | -9 |
| 151 | -17 | 51 | -7 |
| 152 | -16 | 50 | -6 |
| 153 | -15 | 51 | -7 |
| 154 | -16 | 51 | -10 |
| 155 | -32 | 63 | -24 |
| 156 | -27 | 62 | -16 |
| 157 | -23 | 58 | -14 |
| 158 | -22 | 57 | -12 |
| 159 | -21 | 57 | -12 |
| 160 | -20 | 57 | -10 |
| 161 | -20 | 58 | -15 |
| 162 | -38 | 70 | -24 |
| 163 | -28 | 64 | -19 |
| 164 | -27 | 63 | -18 |
| 165 | -27 | 64 | -18 |
| 166 | -24 | 62 | -15 |
| 167 | -40 | 75 | -32 |
| 168 | -33 | 70 | -25 |
| 169 | -32 | 69 | -23 |
| 170 | -31 | 68 | -22 |
| 171 | -30 | 67 | -22 |
| 172 | -30 | 68 | -21 |
| 173 | -32 | 71 | -32 |
| 174 | -40 | 77 | -32 |
| 175 | -39 | 75 | -29 |
| 176 | -37 | 74 | -27 |
| 177 | -36 | 73 | -27 |
| 178 | -35 | 72 | -27 |
| 179 | -35 | 72 | -25 |
| 180 | -52 | 86 | -40 |
| 181 | -41 | 79 | -33 |
| 182 | -40 | 78 | -31 |
| 183 | -39 | 77 | -30 |
| 184 | -39 | 76 | -29 |
| 185 | -37 | 76 | -26 |
| 186 | -55 | 88 | -42 |
| 187 | -46 | 84 | -37 |
| 188 | -45 | 83 | -35 |
| 189 | -44 | 82 | -34 |
| 190 | -43 | 82 | -32 |
| 191 | -41 | 81 | -32 |
| 192 | -42 | 82 | -37 |
| 193 | -53 | 94 | -43 |
| 194 | -48 | 88 | -40 |
| 195 | -47 | 87 | -38 |
| 196 | -47 | 86 | -37 |
| 197 | -44 | 83 | -31 |
| 198 | -43 | 84 | -33 |
| 199 | -43 | 81 | -34 |
| 200 | -56 | 96 | -46 |
| 201 | -55 | 94 | -46 |
| 202 | -54 | 93 | -44 |
| 203 | -53 | 91 | -43 |
| 204 | -50 | 91 | -43 |
| 205 | -66 | 104 | -50 |
| 206 | -61 | 101 | -51 |
| 207 | -59 | 97 | -49 |
| 208 | -55 | 99 | -45 |
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| 210 | -66 | 107 | -57 |
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| 212 | -65 | 106 | -53 |
| 213 | -62 | 104 | -51 |
| 214 | -62 | 104 | -50 |
| 215 | -61 | 103 | -50 |
| 216 | -60 | 102 | -49 |
| 217 | -59 | 101 | -49 |
| 218 | -58 | 101 | -48 |
| 219 | -64 | 109 | -63 |
| 220 | -65 | 108 | -60 |
| 221 | -65 | 109 | -55 |
| 222 | -63 | 107 | -52 |
| 223 | -61 | 107 | -53 |
| 224 | -75 | 120 | -72 |
| 225 | -73 | 117 | -63 |
| 226 | -72 | 115 | -63 |
| 227 | -76 | 124 | -78 |
| 228 | -80 | 124 | -70 |
| 229 | -78 | 122 | -66 |
| 230 | -77 | 120 | -67 |
| 231 | -74 | 119 | -62 |
| 232 | -78 | 127 | -77 |
| 233 | -83 | 126 | -71 |
| 234 | -82 | 126 | -70 |
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| 236 | -78 | 124 | -67 |
| 237 | -76 | 122 | -66 |
| 238 | -76 | 122 | -66 |
| 239 | -97 | 138 | -78 |
| 240 | -82 | 128 | -72 |
| 241 | -80 | 125 | -72 |
| 242 | -78 | 125 | -67 |
| 243 | -77 | 124 | -65 |
| 244 | -76 | 123 | -64 |
| 245 | -75 | 123 | -63 |
| 246 | -75 | 123 | -62 |
| 247 | -74 | 122 | -62 |
| 248 | -73 | 122 | -58 |
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| 252 | -68 | 119 | -57 |
| 253 | -67 | 118 | -54 |
| 254 | -69 | 119 | -56 |
| 255 | -86 | 130 | -59 |
| 256 | -82 | 128 | -58 |
| 257 | -70 | 120 | -59 |
| 258 | -70 | 119 | -58 |
| 259 | -70 | 120 | -58 |
| 260 | -68 | 117 | -57 |
| 261 | -67 | 117 | -57 |
| 262 | -66 | 116 | -57 |
| 263 | -65 | 116 | -58 |
| 264 | -89 | 133 | -65 |
| 265 | -83 | 130 | -63 |
| 266 | -74 | 124 | -63 |
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| 271 | -72 | 124 | -62 |
| 272 | -71 | 124 | -61 |
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| 274 | -68 | 121 | -58 |
| 275 | -68 | 121 | -59 |
| 276 | -80 | 132 | -67 |
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| 278 | -77 | 131 | -70 |
| 279 | -78 | 131 | -68 |
| 280 | -77 | 130 | -66 |
| 281 | -76 | 130 | -66 |
| 282 | -73 | 127 | -64 |
| 283 | -73 | 127 | -64 |
| 284 | -78 | 134 | -80 |
| 285 | -84 | 137 | -73 |
| 286 | -83 | 137 | -72 |
| 287 | -82 | 137 | -71 |
| 288 | -81 | 137 | -70 |
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| 290 | -77 | 133 | -70 |
| 291 | -84 | 137 | -74 |
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| 293 | -92 | 144 | -75 |
| 294 | -87 | 143 | -75 |
| 295 | -86 | 142 | -73 |
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| 297 | -82 | 139 | -72 |
| 298 | -82 | 139 | -71 |
| 299 | -104 | 158 | -85 |
| 300 | -93 | 148 | -79 |
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| 302 | -88 | 146 | -76 |
| 303 | -87 | 145 | -74 |
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| 323 | -87 | 152 | -72 |
| 324 | -87 | 151 | -81 |
| 325 | -95 | 158 | -86 |
| 326 | -103 | 159 | -88 |
| 327 | -101 | 162 | -78 |
| 328 | -93 | 156 | -79 |
| 329 | -91 | 156 | -78 |
| 330 | -88 | 152 | -69 |
| 331 | -85 | 151 | -68 |
| 332 | -80 | 145 | -67 |
| 333 | -76 | 138 | -57 |
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| 335 | -91 | 158 | -81 |
| 336 | -100 | 169 | -80 |
| 337 | -109 | 173 | -77 |
| 338 | -79 | 144 | -67 |
| 339 | -91 | 155 | -79 |
| 340 | -85 | 153 | -77 |
| 341 | -84 | 154 | -71 |
| 342 | -84 | 154 | -72 |
| 343 | -81 | 154 | -70 |
| 344 | -82 | 153 | -70 |
| 345 | -81 | 152 | -70 |
| 346 | -77 | 150 | -69 |
| 347 | -78 | 150 | -67 |
| 348 | -78 | 150 | -69 |
| 349 | -76 | 149 | -69 |
| 350 | -76 | 149 | -67 |
| 351 | -74 | 149 | -66 |
| 352 | -76 | 150 | -67 |
| 353 | -74 | 150 | -69 |
| 354 | -69 | 150 | -66 |
| 355 | -75 | 150 | -64 |
| 356 | -74 | 150 | -63 |
| 357 | -74 | 150 | -64 |
| 358 | -73 | 150 | -63 |
| 359 | -73 | 150 | -63 |
| 360 | -72 | 148 | -63 |
| 361 | -68 | 146 | -63 |
| 362 | -69 | 145 | -62 |
| 363 | -67 | 146 | -62 |
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| 365 | -64 | 145 | -63 |
| 366 | -64 | 147 | -61 |
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| 368 | -68 | 147 | -58 |
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| 379 | -65 | 147 | -54 |
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| 381 | -64 | 146 | -55 |
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| 383 | -61 | 143 | -55 |
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| 402 | -53 | 144 | -46 |
| 403 | -51 | 143 | -42 |
| 404 | -55 | 144 | -46 |
| 405 | -55 | 145 | -46 |
| 406 | -55 | 144 | -46 |
| 407 | -55 | 144 | -47 |
| 408 | -55 | 143 | -46 |
| 409 | -56 | 144 | -47 |
| 410 | -55 | 143 | -46 |
| 411 | -51 | 141 | -46 |
| 412 | -52 | 141 | -47 |
| 413 | -53 | 143 | -47 |
| 414 | -54 | 143 | -45 |
| 415 | -50 | 140 | -45 |
| 416 | -59 | 148 | -58 |
| 417 | -58 | 148 | -51 |
| 418 | -59 | 149 | -50 |
| 419 | -59 | 149 | -50 |
| 420 | -59 | 149 | -52 |
| 421 | -60 | 150 | -50 |
| 422 | -53 | 143 | -47 |
| 423 | -53 | 143 | -48 |
| 424 | -51 | 142 | -47 |
| 425 | -66 | 154 | -62 |
| 426 | -63 | 152 | -59 |
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| 428 | -64 | 153 | -57 |
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| 430 | -65 | 153 | -57 |
| 431 | -65 | 152 | -57 |
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| 437 | -62 | 151 | -55 |
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| 440 | -70 | 160 | -77 |
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| 442 | -70 | 159 | -64 |
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| 444 | -72 | 163 | -62 |
| 445 | -70 | 161 | -59 |
| 446 | -73 | 164 | -61 |

| | | | |
|---|---|---|---|
| 447 | -71 | 163 | -61 |
| 448 | -72 | 163 | -60 |
| 449 | -69 | 161 | -59 |
| 450 | -70 | 162 | -58 |
| 451 | -70 | 162 | -58 |
| 452 | -67 | 161 | -53 |
| 453 | -69 | 162 | -57 |
| 454 | -68 | 161 | -56 |
| 455 | -68 | 162 | -55 |
| 456 | -67 | 161 | -56 |
| 457 | -65 | 160 | -53 |
| 458 | -69 | 165 | -66 |
| 459 | -70 | 165 | -65 |
| 460 | -82 | 173 | -51 |
| 461 | -69 | 164 | -61 |
| 462 | -72 | 167 | -59 |
| 463 | -72 | 167 | -58 |
| 464 | -72 | 167 | -57 |
| 465 | -71 | 166 | -57 |
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| 467 | -71 | 166 | -56 |
| 468 | -71 | 166 | -56 |
| 469 | -71 | 165 | -56 |
| 470 | -70 | 165 | -55 |
| 471 | -71 | 165 | -56 |
| 472 | -67 | 162 | -57 |
| 473 | -69 | 164 | -57 |
| 474 | -69 | 162 | -55 |
| 475 | -68 | 163 | -55 |
| 476 | -66 | 162 | -55 |
| 477 | -67 | 163 | -55 |
| 478 | -64 | 163 | -50 |
| 479 | -67 | 162 | -52 |
| 480 | -68 | 162 | -52 |
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| 489 | -64 | 162 | -50 |
| 490 | -59 | 159 | -49 |
| 491 | -63 | 162 | -49 |
| 492 | -63 | 162 | -46 |
| 493 | -59 | 161 | -44 |
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| 496 | -66 | 163 | -49 |
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| 535 | -75 | 176 | -55 |
| 536 | -74 | 175 | -55 |
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| 541 | -71 | 172 | -52 |
| 542 | -70 | 172 | -51 |
| 543 | -71 | 173 | -51 |
| 544 | -69 | 171 | -51 |
| 545 | -69 | 171 | -51 |
| 546 | -69 | 170 | -52 |
| 547 | -66 | 168 | -50 |
| 548 | -67 | 169 | -50 |
| 549 | -67 | 170 | -59 |
| 550 | -72 | 176 | -57 |
| 551 | -76 | 176 | -58 |
| 552 | -75 | 176 | -57 |
| 553 | -74 | 175 | -57 |
| 554 | -74 | 174 | -57 |
| 555 | -73 | 174 | -56 |
| 556 | -72 | 173 | -56 |
| 557 | -71 | 173 | -55 |
| 558 | -71 | 172 | -55 |
| 559 | -69 | 169 | -54 |
| 560 | -68 | 170 | -54 |
| 561 | -67 | 169 | -53 |
| 562 | -67 | 168 | -56 |
| 563 | -77 | 179 | -54 |
| 564 | -88 | 183 | -55 |
| 565 | -71 | 174 | -57 |
| 566 | -71 | 174 | -57 |
| 567 | -70 | 173 | -55 |
| 568 | -69 | 172 | -55 |
| 569 | -68 | 171 | -54 |
| 570 | -70 | 173 | -54 |
| 571 | -68 | 172 | -53 |
| 572 | -67 | 172 | -52 |
| 573 | -66 | 171 | -52 |
| 574 | -66 | 170 | -52 |
| 575 | -65 | 170 | -50 |
| 576 | -65 | 169 | -50 |
| 577 | -64 | 168 | -49 |
| 578 | -62 | 168 | -54 |
| 579 | -65 | 167 | -53 |
| 580 | -69 | 172 | -50 |
| 581 | -66 | 170 | -51 |
| 582 | -66 | 170 | -50 |
| 583 | -66 | 169 | -50 |
| 584 | -65 | 168 | -50 |
| 585 | -65 | 168 | -48 |
| 586 | -64 | 168 | -47 |
| 587 | -63 | 168 | -46 |
| 588 | -63 | 167 | -46 |
| 589 | -61 | 166 | -44 |
| 590 | -57 | 164 | -44 |
| 591 | -59 | 165 | -44 |
| 592 | -59 | 165 | -45 |
| 593 | -59 | 165 | -44 |
| 594 | -60 | 165 | -45 |
| 595 | -57 | 164 | -43 |
| 596 | -57 | 163 | -43 |
| 597 | -58 | 163 | -43 |
| 598 | -57 | 166 | -54 |
| 599 | -57 | 168 | -51 |
| 600 | -68 | 171 | -55 |
| 601 | -60 | 167 | -43 |
| 602 | -63 | 167 | -46 |
| 603 | -62 | 167 | -46 |
| 604 | -60 | 166 | -46 |
| 605 | -61 | 165 | -45 |
| 606 | -60 | 165 | -45 |
| 607 | -58 | 164 | -42 |
| 608 | -56 | 163 | -43 |
| 609 | -57 | 162 | -43 |
| 610 | -57 | 163 | -44 |
| 611 | -54 | 160 | -47 |
| 612 | -55 | 165 | -46 |
| 613 | -55 | 162 | -41 |
| 614 | -54 | 162 | -38 |
| 615 | -51 | 160 | -36 |
| 616 | -50 | 158 | -35 |
| 617 | -49 | 159 | -36 |
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| 619 | -49 | 161 | -41 |
| 620 | -54 | 163 | -45 |
| 621 | -51 | 160 | -31 |
| 622 | -50 | 159 | -35 |
| 623 | -46 | 157 | -32 |
| 624 | -46 | 156 | -31 |
| 625 | -46 | 156 | -30 |
| 626 | -45 | 155 | -29 |
| 627 | -42 | 156 | -28 |
| 628 | -41 | 152 | -28 |
| 629 | -40 | 151 | -30 |
| 630 | -42 | 155 | -34 |
| 631 | -48 | 153 | -21 |
| 632 | -28 | 135 | -10 |
| 633 | -17 | 128 | -3 |
| 634 | -14 | 125 | -1 |
| 635 | -9 | 121 | 2 |
| 636 | -10 | 121 | 2 |
| 637 | -9 | 119 | 1 |
| 638 | -9 | 119 | 2 |
| 639 | -8 | 118 | 4 |
| 640 | -7 | 118 | 5 |
| 641 | -7 | 117 | 6 |
| 642 | -6 | 117 | 7 |
| 643 | -6 | 118 | 10 |
| 644 | -5 | 117 | 10 |
| 645 | -5 | 118 | 11 |
| 646 | -5 | 117 | 10 |
| 647 | -4 | 116 | 11 |
| 648 | -4 | 116 | 11 |
| 649 | -4 | 116 | 12 |
| 650 | -4 | 116 | 11 |
| 651 | -4 | 116 | 12 |
| 652 | -4 | 116 | 12 |
| 653 | -3 | 115 | 12 |
| 654 | -2 | 115 | 13 |
| 655 | -2 | 115 | 13 |
| 656 | -1 | 114 | 13 |
| 657 | -2 | 114 | 12 |
| 658 | -1 | 115 | 15 |
| 659 | -2 | 115 | 13 |
| 660 | -2 | 115 | 13 |
| 661 | -1 | 114 | 13 |
| 662 | -1 | 114 | 13 |
| 663 | -1 | 114 | 14 |
| 664 | 0 | 114 | 14 |
| 665 | 0 | 115 | 10 |
| 666 | -5 | 119 | 2 |
| 667 | -3 | 120 | 5 |
| 668 | -3 | 117 | 12 |
| 669 | -1 | 116 | 13 |
| 670 | 5 | 111 | 18 |
| 671 | 2 | 113 | 17 |
| 672 | 3 | 112 | 17 |
| 673 | 3 | 112 | 18 |
| 674 | 12 | 107 | 19 |
| 675 | 6 | 110 | 17 |
| 676 | 5 | 110 | 17 |
| 677 | 7 | 109 | 18 |
| 678 | 7 | 109 | 18 |
| 679 | 5 | 113 | 5 |
| 680 | 3 | 117 | 17 |
| 681 | 2 | 114 | 15 |
| 682 | 4 | 112 | 17 |
| 683 | 4 | 112 | 16 |
| 684 | 4 | 113 | 17 |
| 685 | 6 | 111 | 17 |
| 686 | 6 | 111 | 18 |
| 687 | 7 | 111 | 18 |
| 688 | 7 | 111 | 18 |
| 689 | 7 | 111 | 19 |
| 690 | 9 | 110 | 18 |
| 691 | 8 | 111 | 19 |
| 692 | 8 | 112 | 20 |
| 693 | 8 | 112 | 21 |
| 694 | 9 | 112 | 21 |
| 695 | 9 | 111 | 20 |
| 696 | 8 | 107 | 20 |
| 697 | 11 | 111 | 22 |
| 698 | 11 | 110 | 21 |
| 699 | 14 | 107 | 20 |
| 700 | 12 | 109 | 20 |
| 701 | 12 | 110 | 22 |
| 702 | 12 | 110 | 21 |
| 703 | 12 | 110 | 21 |
| 704 | 13 | 110 | 13 |
| 705 | 10 | 112 | 11 |
| 706 | 0 | 119 | 9 |
| 707 | 5 | 114 | 19 |
| 708 | 15 | 109 | 21 |
| 709 | 15 | 108 | 24 |
| 710 | 15 | 109 | 25 |
| 711 | 15 | 109 | 26 |
| 712 | 15 | 108 | 26 |
| 713 | 15 | 109 | 25 |
| 714 | 16 | 106 | 24 |
| 715 | 18 | 105 | 24 |
| 716 | 15 | 107 | 23 |
| 717 | 15 | 107 | 23 |
| 718 | 15 | 108 | 23 |
| 719 | 14 | 110 | 22 |
| 720 | 17 | 111 | 15 |
| 721 | 20 | 108 | 16 |
| 722 | 18 | 108 | 28 |
| 723 | 18 | 108 | 30 |
| 724 | 19 | 107 | 31 |
| 725 | 20 | 107 | 31 |
| 726 | 22 | 103 | 34 |
| 727 | 21 | 104 | 31 |
| 728 | 19 | 109 | 28 |
| 729 | 20 | 106 | 32 |
| 730 | 24 | 105 | 30 |
| 731 | 22 | 105 | 31 |
| 732 | 22 | 105 | 33 |
| 733 | 21 | 106 | 31 |
| 734 | 22 | 107 | 31 |
| 735 | 20 | 109 | 31 |
| 736 | 18 | 110 | 30 |
| 737 | 19 | 108 | 31 |
| 738 | 20 | 109 | 31 |
| 739 | 20 | 110 | 31 |
| 740 | 20 | 108 | 32 |
| 741 | 27 | 104 | 39 |
| 742 | 28 | 104 | 35 |
| 743 | 27 | 107 | 34 |
| 744 | 27 | 108 | 36 |
| 745 | 26 | 108 | 28 |
| 746 | 27 | 107 | 27 |
| 747 | 30 | 104 | 41 |
| 748 | 30 | 105 | 47 |
| 749 | 34 | 104 | 38 |
| 750 | 33 | 103 | 36 |
| 751 | 28 | 104 | 39 |
| 752 | 29 | 103 | 39 |
| 753 | 29 | 98 | 39 |
| 754 | 29 | 102 | 37 |
| 755 | 32 | 98 | 39 |
| 756 | 29 | 102 | 39 |
| 757 | 29 | 102 | 38 |
| 758 | 29 | 102 | 39 |
| 759 | 29 | 102 | 39 |
| 760 | 29 | 101 | 38 |
| 761 | 31 | 96 | 40 |
| 762 | 30 | 99 | 39 |
| 763 | 29 | 101 | 38 |
| 764 | 28 | 102 | 39 |
| 765 | 29 | 102 | 39 |
| 766 | 30 | 100 | 38 |
| 767 | 32 | 99 | 42 |
| 768 | 31 | 99 | 40 |
| 769 | 33 | 100 | 39 |
| 770 | 34 | 99 | 43 |
| 771 | 35 | 100 | 41 |
| 772 | 29 | 102 | 37 |
| 773 | 32 | 98 | 36 |
| 774 | 31 | 100 | 38 |
| 775 | 31 | 101 | 39 |
| 776 | 31 | 100 | 39 |
| 777 | 31 | 101 | 38 |
| 778 | 31 | 101 | 41 |
| 779 | 30 | 101 | 39 |
| 780 | 27 | 103 | 39 |
| 781 | 28 | 103 | 38 |
| 782 | 34 | 98 | 40 |

| | | | |
|---|---|---|---|
| 783 | 29 | 101 | 39 |
| 784 | 28 | 103 | 39 |
| 785 | 31 | 100 | 44 |
| 786 | 29 | 102 | 40 |
| 787 | 32 | 100 | 43 |
| 788 | 37 | 98 | 43 |
| 789 | 36 | 99 | 47 |
| 790 | 30 | 101 | 42 |
| 791 | 30 | 100 | 42 |
| 792 | 31 | 100 | 46 |
| 793 | 32 | 100 | 43 |
| 794 | 32 | 100 | 43 |
| 795 | 32 | 100 | 43 |
| 796 | 32 | 100 | 43 |
| 797 | 36 | 98 | 46 |
| 798 | 40 | 96 | 48 |
| 799 | 42 | 89 | 46 |
| 800 | 35 | 101 | 42 |
| 801 | 37 | 101 | 45 |
| 802 | 32 | 102 | 44 |
| 803 | 31 | 103 | 44 |
| 804 | 32 | 102 | 45 |
| 805 | 32 | 103 | 45 |
| 806 | 33 | 103 | 46 |
| 807 | 33 | 102 | 46 |
| 808 | 35 | 97 | 49 |
| 809 | 37 | 100 | 47 |
| 810 | 36 | 102 | 48 |
| 811 | 36 | 98 | 49 |
| 812 | 40 | 99 | 51 |
| 813 | 40 | 102 | 52 |
| 814 | 40 | 103 | 48 |
| 815 | 36 | 105 | 61 |

| | | | |
|---|---|---|---|
| 816 | 48 | 91 | 63 |
| 817 | 36 | 105 | 48 |
| 818 | 34 | 105 | 51 |
| 819 | 37 | 105 | 54 |
| 820 | 38 | 100 | 55 |
| 821 | 35 | 105 | 50 |
| 822 | 34 | 107 | 49 |
| 823 | 34 | 107 | 49 |
| 824 | 35 | 107 | 49 |
| 825 | 34 | 107 | 49 |
| 826 | 34 | 109 | 49 |
| 827 | 34 | 106 | 49 |
| 828 | 36 | 105 | 49 |
| 829 | 37 | 102 | 53 |
| 830 | 35 | 106 | 48 |
| 831 | 36 | 105 | 50 |
| 832 | 38 | 103 | 50 |
| 833 | 36 | 106 | 51 |
| 834 | 35 | 107 | 49 |
| 835 | 35 | 106 | 48 |
| 836 | 39 | 105 | 49 |
| 837 | 34 | 106 | 48 |
| 838 | 34 | 106 | 47 |
| 839 | 34 | 107 | 47 |
| 840 | 34 | 103 | 45 |
| 841 | 37 | 107 | 49 |
| 842 | 34 | 107 | 47 |
| 843 | 34 | 107 | 47 |
| 844 | 34 | 107 | 46 |
| 845 | 34 | 107 | 47 |
| 846 | 34 | 107 | 47 |
| 847 | 34 | 107 | 47 |
| 848 | 34 | 107 | 46 |

| | | | |
|---|---|---|---|
| 849 | 34 | 106 | 46 |
| 850 | 34 | 106 | 45 |
| 851 | 34 | 106 | 45 |
| 852 | 34 | 106 | 45 |
| 853 | 34 | 105 | 42 |
| 854 | 36 | 102 | 43 |
| 855 | 37 | 101 | 44 |
| 856 | 38 | 99 | 38 |
| 857 | 35 | 102 | 28 |
| 858 | 35 | 102 | 40 |
| 859 | 36 | 102 | 43 |
| 860 | 39 | 98 | 47 |
| 861 | 39 | 101 | 43 |
| 862 | 39 | 101 | 49 |
| 863 | 36 | 99 | 43 |
| 864 | 38 | 102 | 44 |
| 865 | 38 | 103 | 49 |
| 866 | 35 | 104 | 47 |
| 867 | 38 | 100 | 45 |
| 868 | 38 | 100 | 44 |
| 869 | 39 | 101 | 34 |
| 870 | 37 | 102 | 35 |
| 871 | 35 | 103 | 33 |
| 872 | 30 | 106 | 39 |
| 873 | 38 | 104 | 48 |
| 874 | 33 | 105 | 42 |
| 875 | 36 | 103 | 48 |
| 876 | 38 | 101 | 48 |
| 877 | 37 | 102 | 48 |
| 878 | 37 | 93 | 48 |
| 879 | 37 | 101 | 48 |

## 9.4 Complete Raw Data for Cadaver 3

### 9.4.1 Mid-Palatal Suture Sensor

| time | 1 | 2 | 3 |
|---|---|---|---|
| 1 | 13 | -5 | 11 |
| 2 | 14 | -4 | 12 |
| 3 | 14 | -4 | 13 |
| 4 | 15 | -3 | 14 |
| 5 | 12 | -4 | 21 |
| 6 | 21 | -2 | 17 |
| 7 | 19 | -3 | 17 |
| 8 | 19 | -3 | 17 |
| 9 | 19 | -2 | 18 |
| 10 | 19 | -2 | 18 |
| 11 | 20 | -2 | 18 |
| 12 | 20 | -2 | 19 |
| 13 | 21 | -2 | 19 |
| 14 | 21 | -2 | 19 |
| 15 | 21 | -1 | 19 |
| 16 | 22 | -2 | 19 |
| 17 | 17 | 0 | 36 |
| 18 | 19 | 3 | 29 |
| 19 | 20 | 2 | 28 |
| 20 | 20 | 2 | 28 |
| 21 | 20 | 2 | 27 |
| 22 | 21 | 2 | 28 |
| 23 | 22 | 3 | 28 |
| 24 | 22 | 3 | 29 |
| 25 | 21 | 5 | 32 |
| 26 | 19 | 8 | 40 |
| 27 | 20 | 7 | 37 |
| 28 | 21 | 6 | 36 |
| 29 | 22 | 6 | 36 |
| 30 | 22 | 6 | 36 |
| 31 | 23 | 6 | 36 |
| 32 | 23 | 6 | 36 |
| 33 | 24 | 8 | 36 |
| 34 | 22 | 8 | 40 |
| 35 | 24 | 6 | 41 |
| 36 | 25 | 3 | 41 |
| 37 | 25 | 9 | 46 |
| 38 | 26 | 9 | 45 |
| 39 | 26 | 9 | 45 |
| 40 | 27 | 9 | 44 |
| 41 | 28 | 8 | 47 |
| 42 | 27 | 6 | 41 |
| 43 | 28 | 6 | 45 |
| 44 | 26 | 9 | 58 |
| 45 | 28 | 16 | 61 |
| 46 | 29 | 14 | 60 |
| 47 | 30 | 14 | 58 |
| 48 | 31 | 14 | 59 |
| 49 | 31 | 14 | 57 |
| 50 | 31 | 7 | 49 |
| 51 | 30 | 19 | 78 |
| 52 | 32 | 21 | 77 |
| 53 | 32 | 18 | 73 |
| 54 | 32 | 17 | 69 |
| 55 | 33 | 16 | 67 |
| 56 | 34 | 12 | 65 |
| 57 | 33 | 9 | 60 |
| 58 | 34 | 25 | 85 |
| 59 | 34 | 21 | 79 |
| 60 | 35 | 19 | 75 |
| 61 | 35 | 17 | 72 |
| 62 | 36 | 16 | 71 |
| 63 | 37 | 13 | 71 |
| 64 | 36 | 17 | 72 |
| 65 | 35 | 26 | 91 |
| 66 | 35 | 22 | 85 |
| 67 | 35 | 20 | 80 |
| 68 | 36 | 19 | 77 |
| 69 | 36 | 21 | 70 |
| 70 | 36 | 20 | 67 |
| 71 | 37 | 23 | 89 |
| 72 | 37 | 27 | 98 |
| 73 | 38 | 24 | 91 |
| 74 | 38 | 22 | 87 |
| 75 | 39 | 20 | 84 |
| 76 | 39 | 19 | 82 |
| 77 | 40 | 16 | 81 |
| 78 | 40 | 12 | 77 |
| 79 | 39 | 15 | 62 |
| 80 | 40 | 34 | 71 |
| 81 | 40 | 25 | 72 |
| 82 | 40 | 21 | 56 |
| 83 | 41 | 18 | 70 |
| 84 | 45 | 29 | 103 |
| 85 | 43 | 25 | 96 |
| 86 | 43 | 23 | 92 |
| 87 | 43 | 22 | 89 |
| 88 | 44 | 21 | 87 |
| 89 | 44 | 20 | 86 |
| 90 | 44 | 20 | 84 |
| 91 | 44 | 19 | 83 |
| 92 | 45 | 19 | 81 |
| 93 | 45 | 18 | 81 |
| 94 | 45 | 18 | 80 |
| 95 | 46 | 18 | 79 |
| 96 | 46 | 18 | 79 |
| 97 | 47 | 18 | 78 |
| 98 | 47 | 18 | 78 |
| 99 | 47 | 18 | 77 |
| 100 | 48 | 17 | 77 |
| 101 | 48 | 17 | 76 |
| 102 | 48 | 17 | 76 |
| 103 | 49 | 17 | 76 |
| 104 | 49 | 17 | 76 |
| 105 | 50 | 17 | 75 |
| 106 | 50 | 17 | 75 |
| 107 | 50 | 17 | 75 |
| 108 | 51 | 17 | 70 |
| 109 | 51 | 17 | 71 |
| 110 | 52 | 17 | 72 |
| 111 | 52 | 17 | 72 |
| 112 | 52 | 18 | 73 |
| 113 | 52 | 17 | 68 |
| 114 | 52 | 16 | 65 |
| 115 | 51 | 17 | 50 |
| 116 | 54 | 19 | 72 |
| 117 | 54 | 19 | 76 |
| 118 | 54 | 19 | 76 |
| 119 | 55 | 19 | 77 |
| 120 | 55 | 19 | 73 |
| 121 | 56 | 19 | 72 |
| 122 | 55 | 19 | 66 |
| 123 | 55 | 18 | 47 |
| 124 | 58 | 19 | 69 |
| 125 | 58 | 18 | 61 |
| 126 | 58 | 20 | 71 |
| 127 | 59 | 20 | 70 |
| 128 | 57 | 19 | 52 |
| 129 | 61 | 22 | 72 |
| 130 | 61 | 21 | 71 |
| 131 | 61 | 21 | 71 |
| 132 | 61 | 22 | 79 |
| 133 | 61 | 22 | 79 |
| 134 | 62 | 22 | 79 |
| 135 | 62 | 22 | 79 |
| 136 | 62 | 22 | 80 |
| 137 | 63 | 22 | 80 |
| 138 | 63 | 22 | 80 |
| 139 | 63 | 22 | 80 |
| 140 | 64 | 22 | 80 |
| 141 | 64 | 22 | 80 |
| 142 | 65 | 22 | 80 |
| 143 | 65 | 22 | 80 |
| 144 | 65 | 22 | 81 |
| 145 | 65 | 22 | 81 |
| 146 | 66 | 21 | 80 |
| 147 | 67 | 21 | 81 |
| 148 | 67 | 22 | 82 |
| 149 | 64 | 20 | 81 |
| 150 | 64 | 22 | 81 |
| 151 | 61 | 17 | 85 |
| 152 | 57 | 18 | 85 |
| 153 | 57 | 17 | 81 |
| 154 | 57 | 20 | 81 |
| 155 | 59 | 19 | 81 |
| 156 | 58 | 17 | 77 |
| 157 | 60 | 15 | 77 |
| 158 | 59 | 19 | 79 |
| 159 | 59 | 19 | 80 |
| 160 | 60 | 19 | 80 |
| 161 | 61 | 18 | 79 |
| 162 | 61 | 18 | 82 |
| 163 | 61 | 21 | 80 |
| 164 | 68 | 27 | 78 |
| 165 | 75 | 34 | 77 |
| 166 | 80 | 33 | 78 |
| 167 | 84 | 31 | 79 |
| 168 | 55 | 15 | 84 |
| 169 | 61 | 20 | 84 |
| 170 | -19 | 5 | 92 |
| 171 | 51 | 21 | 81 |
| 172 | 53 | 19 | 80 |
| 173 | 52 | 19 | 80 |
| 174 | 52 | 19 | 81 |
| 175 | 52 | 19 | 81 |
| 176 | 52 | 19 | 81 |
| 177 | 52 | 20 | 81 |
| 178 | 51 | 19 | 82 |
| 179 | 46 | 18 | 83 |
| 180 | 50 | 19 | 83 |
| 181 | 63 | 29 | 81 |
| 182 | 80 | 34 | 80 |
| 183 | 84 | 34 | 81 |
| 184 | 87 | 33 | 81 |
| 185 | 54 | 19 | 85 |
| 186 | 51 | 20 | 85 |
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| 1507 | 347 | 20 | 553 |
| 1508 | 347 | 20 | 554 |
| 1509 | 347 | 19 | 554 |
| 1510 | 347 | 19 | 553 |
| 1511 | 344 | 14 | 552 |
| 1512 | 342 | 9 | 548 |
| 1513 | 342 | 5 | 513 |
| 1514 | 341 | -3 | 490 |
| 1515 | 341 | 3 | 481 |
| 1516 | 343 | 17 | 549 |
| 1517 | 346 | 18 | 549 |
| 1518 | 347 | 15 | 545 |
| 1519 | 347 | 9 | 537 |
| 1520 | 347 | 15 | 545 |

### *9.4.2 Intermaxillary Suture Sensor*

| time | 1 | 2 | 3 |
|---|---|---|---|
| 1 | -9 | 1 | 65 |
| 2 | -13 | 2 | 63 |
| 3 | -15 | 1 | 61 |
| 4 | -15 | 1 | 57 |
| 5 | -15 | 1 | 56 |
| 6 | -15 | 2 | 54 |
| 7 | -15 | 2 | 53 |
| 8 | -11 | 3 | 48 |
| 9 | -18 | 1 | 49 |
| 10 | -17 | 5 | 46 |
| 11 | -9 | 4 | 40 |
| 12 | 2 | 8 | 32 |
| 13 | -5 | 12 | 35 |
| 14 | 1 | 9 | 29 |
| 15 | -14 | 4 | 39 |
| 16 | -12 | 4 | 37 |
| 17 | -12 | 4 | 36 |
| 18 | -12 | 4 | 34 |
| 19 | -10 | 4 | 34 |
| 20 | -8 | 6 | 30 |
| 21 | -15 | 7 | 24 |
| 22 | -2 | 6 | 24 |
| 23 | -14 | 6 | 29 |
| 24 | -13 | 5 | 28 |
| 25 | -12 | 5 | 27 |
| 26 | -9 | 11 | 22 |
| 27 | 6 | 40 | 22 |
| 28 | -3 | -67 | -30 |
| 29 | 2 | -77 | -19 |
| 30 | 22 | 165 | -48 |
| 31 | 42 | 170 | -46 |
| 32 | -4 | 162 | -34 |
| 33 | -3 | 162 | -34 |
| 34 | -2 | 162 | -34 |
| 35 | 7 | 167 | -37 |
| 36 | -2 | 161 | -33 |
| 37 | 12 | 165 | -44 |
| 38 | 17 | 170 | -47 |
| 39 | -4 | 164 | -33 |
| 40 | -3 | 164 | -32 |
| 41 | -3 | 164 | -32 |
| 42 | -3 | 164 | -32 |
| 43 | 4 | 167 | -34 |
| 44 | 2 | 163 | -37 |
| 45 | 1 | 162 | -40 |
| 46 | -2 | 165 | -32 |
| 47 | -2 | 165 | -32 |
| 48 | -2 | 165 | -32 |
| 49 | -2 | 165 | -32 |
| 50 | -2 | 165 | -32 |
| 51 | 8 | 168 | -35 |
| 52 | 13 | 165 | -42 |
| 53 | 33 | 173 | -52 |
| 54 | 43 | 176 | -60 |
| 55 | 30 | 175 | -59 |
| 56 | 2 | 167 | -34 |
| 57 | 0 | 166 | -33 |
| 58 | 0 | 166 | -33 |
| 59 | 0 | 167 | -33 |
| 60 | 0 | 167 | -33 |
| 61 | 0 | 166 | -33 |
| 62 | 0 | 167 | -33 |
| 63 | 12 | 170 | -37 |
| 64 | 9 | 170 | -35 |
| 65 | 4 | 169 | -39 |
| 66 | 3 | 168 | -34 |
| 67 | 15 | 170 | -40 |
| 68 | 16 | 180 | -57 |
| 69 | 20 | 172 | -39 |
| 70 | 2 | 168 | -35 |
| 71 | 2 | 168 | -34 |
| 72 | 2 | 168 | -34 |
| 73 | 2 | 169 | -33 |
| 74 | 13 | 171 | -37 |
| 75 | 15 | 172 | -43 |
| 76 | 6 | 170 | -34 |
| 77 | 8 | 172 | -37 |
| 78 | 12 | 171 | -35 |
| 79 | 15 | 172 | -37 |
| 80 | 23 | 178 | -45 |
| 81 | 61 | 180 | -72 |
| 82 | 10 | 169 | -41 |
| 83 | 9 | 170 | -40 |
| 84 | 8 | 170 | -39 |
| 85 | 8 | 170 | -39 |
| 86 | 8 | 170 | -39 |
| 87 | 8 | 168 | -38 |
| 88 | 7 | 168 | -37 |
| 89 | 25 | 173 | -49 |
| 90 | 13 | 169 | -49 |
| 91 | 12 | 169 | -48 |
| 92 | 11 | 170 | -48 |
| 93 | 11 | 170 | -47 |
| 94 | 16 | 171 | -49 |
| 95 | 15 | 171 | -48 |
| 96 | 12 | 170 | -48 |
| 97 | 27 | 170 | -61 |
| 98 | 30 | 172 | -64 |
| 99 | 28 | 171 | -62 |
| 100 | 27 | 172 | -61 |
| 101 | 26 | 171 | -62 |
| 102 | 28 | 171 | -60 |
| 103 | 29 | 172 | -61 |
| 104 | 22 | 171 | -55 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 105 | 16 | 168 | -62 | 217 | 438 | 158 | -391 | 329 | 560 | 76 | -326 |
| 106 | 22 | 168 | -58 | 218 | 452 | 140 | -392 | 330 | 549 | 74 | -319 |
| 107 | 36 | 171 | -59 | 219 | 466 | 131 | -415 | 331 | 543 | 76 | -312 |
| 108 | 26 | 172 | -59 | 220 | 475 | 133 | -410 | 332 | 537 | 76 | -307 |
| 109 | 26 | 172 | -59 | 221 | 482 | 127 | -417 | 333 | 533 | 76 | -304 |
| 110 | 25 | 172 | -58 | 222 | 478 | 127 | -413 | 334 | 530 | 77 | -300 |
| 111 | 25 | 172 | -58 | 223 | 475 | 129 | -409 | 335 | 527 | 78 | -298 |
| 112 | 35 | 175 | -60 | 224 | 472 | 130 | -407 | 336 | 522 | 78 | -292 |
| 113 | 30 | 172 | -56 | 225 | 470 | 130 | -404 | 337 | 521 | 80 | -294 |
| 114 | 40 | 176 | -77 | 226 | 464 | 126 | -392 | 338 | 538 | 109 | -308 |
| 115 | 66 | 175 | -88 | 227 | 486 | 142 | -408 | 339 | 583 | 59 | -342 |
| 116 | 68 | 175 | -94 | 228 | 474 | 128 | -402 | 340 | 562 | 65 | -327 |
| 117 | 65 | 174 | -92 | 229 | 470 | 128 | -400 | 341 | 551 | 63 | -320 |
| 118 | 63 | 174 | -91 | 230 | 497 | 138 | -421 | 342 | 544 | 66 | -312 |
| 119 | 62 | 174 | -91 | 231 | 536 | 125 | -433 | 343 | 539 | 67 | -307 |
| 120 | 61 | 174 | -90 | 232 | 507 | 127 | -428 | 344 | 534 | 70 | -302 |
| 121 | 63 | 174 | -88 | 233 | 504 | 127 | -426 | 345 | 533 | 78 | -296 |
| 122 | 51 | 171 | -84 | 234 | 501 | 128 | -423 | 346 | 598 | 71 | -351 |
| 123 | 68 | 173 | -90 | 235 | 499 | 128 | -421 | 347 | 563 | 36 | -338 |
| 124 | 95 | 178 | -127 | 236 | 497 | 129 | -419 | 348 | 558 | 52 | -323 |
| 125 | 106 | 173 | -126 | 237 | 494 | 129 | -417 | 349 | 547 | 54 | -313 |
| 126 | 103 | 173 | -125 | 238 | 492 | 129 | -416 | 350 | 538 | 56 | -306 |
| 127 | 102 | 173 | -124 | 239 | 492 | 129 | -416 | 351 | 533 | 58 | -300 |
| 128 | 101 | 172 | -123 | 240 | 479 | 120 | -403 | 352 | 523 | 50 | -290 |
| 129 | 102 | 173 | -124 | 241 | 486 | 138 | -414 | 353 | 537 | 77 | -305 |
| 130 | 96 | 166 | -116 | 242 | 494 | 133 | -414 | 354 | 615 | 48 | -362 |
| 131 | 93 | 165 | -115 | 243 | 490 | 131 | -413 | 355 | 548 | 25 | -315 |
| 132 | 79 | 155 | -110 | 244 | 488 | 132 | -410 | 356 | 532 | 28 | -305 |
| 133 | 91 | 165 | -111 | 245 | 487 | 132 | -415 | 357 | 523 | 32 | -297 |
| 134 | 103 | 175 | -136 | 246 | 495 | 140 | -448 | 358 | 517 | 35 | -292 |
| 135 | 112 | 182 | -127 | 247 | 515 | 140 | -444 | 359 | 540 | 65 | -350 |
| 136 | 132 | 175 | -150 | 248 | 519 | 133 | -443 | 360 | 567 | -6 | -312 |
| 137 | 123 | 175 | -148 | 249 | 531 | 127 | -440 | 361 | 542 | 5 | -302 |
| 138 | 121 | 175 | -147 | 250 | 528 | 129 | -436 | 362 | 535 | 9 | -297 |
| 139 | 120 | 175 | -146 | 251 | 525 | 148 | -427 | 363 | 530 | 13 | -294 |
| 140 | 120 | 175 | -146 | 252 | 513 | 132 | -426 | 364 | 513 | 7 | -277 |
| 141 | 119 | 174 | -145 | 253 | 531 | 125 | -444 | 365 | 512 | 11 | -285 |
| 142 | 127 | 178 | -147 | 254 | 534 | 127 | -438 | 366 | 509 | 18 | -288 |
| 143 | 109 | 175 | -143 | 255 | 530 | 127 | -435 | 367 | 506 | 20 | -283 |
| 144 | 159 | 184 | -182 | 256 | 526 | 127 | -432 | 368 | 502 | 21 | -282 |
| 145 | 158 | 169 | -186 | 257 | 524 | 127 | -430 | 369 | 499 | 24 | -277 |
| 146 | 206 | 178 | -195 | 258 | 522 | 128 | -429 | 370 | 495 | 24 | -275 |
| 147 | 171 | 172 | -191 | 259 | 519 | 128 | -427 | 371 | 492 | 25 | -273 |
| 148 | 170 | 173 | -189 | 260 | 518 | 128 | -425 | 372 | 489 | 26 | -271 |
| 149 | 168 | 172 | -188 | 261 | 517 | 129 | -425 | 373 | 486 | 26 | -269 |
| 150 | 167 | 172 | -187 | 262 | 513 | 127 | -420 | 374 | 480 | 21 | -266 |
| 151 | 167 | 172 | -187 | 263 | 505 | 125 | -413 | 375 | 475 | 22 | -266 |
| 152 | 170 | 173 | -187 | 264 | 498 | 112 | -402 | 376 | 475 | 22 | -263 |
| 153 | 164 | 166 | -184 | 265 | 509 | 130 | -418 | 377 | 472 | 24 | -263 |
| 154 | 165 | 170 | -179 | 266 | 508 | 131 | -417 | 378 | 464 | 8 | -252 |
| 155 | 158 | 167 | -179 | 267 | 506 | 131 | -416 | 379 | 472 | 30 | -264 |
| 156 | 146 | 171 | -179 | 268 | 508 | 132 | -416 | 380 | 470 | 31 | -262 |
| 157 | 199 | 166 | -218 | 269 | 500 | 134 | -411 | 381 | 468 | 31 | -260 |
| 158 | 242 | 174 | -243 | 270 | 507 | 132 | -413 | 382 | 466 | 32 | -259 |
| 159 | 228 | 163 | -237 | 271 | 549 | 148 | -475 | 383 | 469 | 36 | -254 |
| 160 | 223 | 163 | -234 | 272 | 548 | 131 | -439 | 384 | 498 | 65 | -274 |
| 161 | 221 | 164 | -231 | 273 | 576 | 140 | -463 | 385 | 511 | 42 | -305 |
| 162 | 219 | 165 | -229 | 274 | 570 | 136 | -451 | 386 | 548 | 37 | -312 |
| 163 | 217 | 162 | -231 | 275 | 566 | 138 | -446 | 387 | 543 | 12 | -304 |
| 164 | 263 | 155 | -270 | 276 | 562 | 138 | -442 | 388 | 518 | 8 | -295 |
| 165 | 278 | 154 | -280 | 277 | 559 | 139 | -439 | 389 | 508 | 5 | -282 |
| 166 | 271 | 155 | -274 | 278 | 553 | 138 | -435 | 390 | 500 | 14 | -281 |
| 167 | 268 | 155 | -270 | 279 | 525 | 140 | -312 | 391 | 495 | 16 | -278 |
| 168 | 267 | 156 | -268 | 280 | 524 | 159 | -312 | 392 | 490 | 18 | -275 |
| 169 | 260 | 152 | -263 | 281 | 508 | 131 | -296 | 393 | 485 | 19 | -272 |
| 170 | 269 | 162 | -266 | 282 | 503 | 130 | -292 | 394 | 482 | 21 | -271 |
| 171 | 311 | 161 | -309 | 283 | 499 | 130 | -289 | 395 | 477 | 21 | -268 |
| 172 | 316 | 149 | -325 | 284 | 495 | 129 | -287 | 396 | 475 | 21 | -259 |
| 173 | 320 | 148 | -307 | 285 | 491 | 131 | -286 | 397 | 474 | 25 | -265 |
| 174 | 315 | 149 | -303 | 286 | 528 | 145 | -314 | 398 | 473 | 33 | -268 |
| 175 | 312 | 150 | -300 | 287 | 549 | 130 | -321 | 399 | 550 | 9 | -323 |
| 176 | 309 | 149 | -298 | 288 | 548 | 117 | -311 | 400 | 569 | -3 | -311 |
| 177 | 308 | 150 | -296 | 289 | 541 | 118 | -307 | 401 | 532 | -6 | -302 |
| 178 | 294 | 139 | -286 | 290 | 534 | 119 | -301 | 402 | 522 | -3 | -297 |
| 179 | 333 | 163 | -345 | 291 | 529 | 119 | -297 | 403 | 515 | 0 | -293 |
| 180 | 331 | 159 | -312 | 292 | 526 | 120 | -295 | 404 | 509 | 3 | -290 |
| 181 | 394 | 155 | -335 | 293 | 520 | 118 | -289 | 405 | 505 | 5 | -288 |
| 182 | 360 | 145 | -334 | 294 | 540 | 133 | -306 | 406 | 502 | 7 | -286 |
| 183 | 355 | 145 | -331 | 295 | 522 | 112 | -289 | 407 | 499 | 8 | -284 |
| 184 | 352 | 146 | -328 | 296 | 518 | 112 | -286 | 408 | 498 | 18 | -280 |
| 185 | 348 | 147 | -325 | 297 | 514 | 113 | -283 | 409 | 556 | -1 | -329 |
| 186 | 346 | 147 | -324 | 298 | 525 | 143 | -300 | 410 | 561 | 10 | -308 |
| 187 | 345 | 148 | -322 | 299 | 554 | 113 | -312 | 411 | 526 | 1 | -299 |
| 188 | 343 | 148 | -321 | 300 | 531 | 85 | -321 | 412 | 521 | -5 | -295 |
| 189 | 335 | 143 | -316 | 301 | 541 | 93 | -315 | 413 | 537 | -2 | -311 |
| 190 | 374 | 165 | -335 | 302 | 537 | 96 | -310 | 414 | 559 | 10 | -317 |
| 191 | 349 | 165 | -371 | 303 | 530 | 97 | -305 | 415 | 540 | -7 | -311 |
| 192 | 370 | 151 | -352 | 304 | 526 | 98 | -301 | 416 | 521 | -10 | -298 |
| 193 | 386 | 142 | -360 | 305 | 531 | 119 | -312 | 417 | 511 | -8 | -290 |
| 194 | 386 | 144 | -354 | 306 | 579 | 92 | -344 | 418 | 503 | -5 | -285 |
| 195 | 382 | 145 | -351 | 307 | 566 | 88 | -332 | 419 | 497 | -4 | -281 |
| 196 | 381 | 146 | -349 | 308 | 559 | 92 | -323 | 420 | 492 | -2 | -278 |
| 197 | 375 | 143 | -347 | 309 | 552 | 93 | -317 | 421 | 487 | -1 | -274 |
| 198 | 425 | 158 | -370 | 310 | 608 | 110 | -351 | 422 | 486 | 2 | -272 |
| 199 | 394 | 135 | -352 | 311 | 591 | 85 | -347 | 423 | 513 | 25 | -279 |
| 200 | 403 | 144 | -367 | 312 | 577 | 84 | -337 | 424 | 478 | 2 | -260 |
| 201 | 401 | 144 | -364 | 313 | 568 | 87 | -329 | 425 | 475 | 20 | -267 |
| 202 | 399 | 142 | -359 | 314 | 561 | 88 | -323 | 426 | 527 | 17 | -302 |
| 203 | 400 | 143 | -361 | 315 | 554 | 87 | -318 | 427 | 551 | 3 | -293 |
| 204 | 399 | 141 | -359 | 316 | 547 | 97 | -309 | 428 | 530 | 2 | -303 |
| 205 | 399 | 142 | -358 | 317 | 537 | 89 | -301 | 429 | 514 | -11 | -284 |
| 206 | 399 | 142 | -357 | 318 | 526 | 65 | -295 | 430 | 499 | -11 | -279 |
| 207 | 398 | 142 | -355 | 319 | 554 | 90 | -319 | 431 | 491 | -9 | -275 |
| 208 | 403 | 159 | -367 | 320 | 561 | 95 | -311 | 432 | 486 | -7 | -271 |
| 209 | 433 | 124 | -387 | 321 | 553 | 85 | -301 | 433 | 480 | -5 | -268 |
| 210 | 444 | 135 | -393 | 322 | 549 | 86 | -320 | 434 | 475 | -3 | -265 |
| 211 | 440 | 133 | -390 | 323 | 539 | 83 | -309 | 435 | 472 | -2 | -263 |
| 212 | 438 | 134 | -387 | 324 | 541 | 97 | -305 | 436 | 472 | 2 | -261 |
| 213 | 437 | 135 | -385 | 325 | 546 | 97 | -319 | 437 | 463 | 3 | -253 |
| 214 | 435 | 135 | -383 | 326 | 543 | 78 | -315 | 438 | 462 | 1 | -255 |
| 215 | 426 | 130 | -381 | 327 | 581 | 105 | -344 | 439 | 460 | 9 | -256 |
| 216 | 443 | 134 | -386 | 328 | 563 | 91 | -331 | 440 | 474 | 19 | -255 |

| | | | |
|---|---|---|---|
| 441 | 464 | 6 | -255 |
| 442 | 555 | -12 | -334 |
| 443 | 525 | -23 | -289 |
| 444 | 504 | -15 | -279 |
| 445 | 490 | -9 | -271 |
| 446 | 478 | -5 | -264 |
| 447 | 467 | 0 | -257 |
| 448 | 456 | 5 | -251 |
| 449 | 443 | 12 | -242 |
| 450 | 426 | 22 | -230 |
| 451 | 153 | 150 | -115 |
| 452 | 166 | 165 | -125 |
| 453 | 163 | 163 | -114 |
| 454 | 151 | 158 | -110 |
| 455 | 143 | 156 | -105 |
| 456 | 145 | 115 | -102 |
| 457 | 72 | 69 | -91 |
| 458 | 112 | 125 | -91 |
| 459 | 113 | 123 | -91 |
| 460 | 113 | 122 | -90 |
| 461 | 112 | 122 | -90 |
| 462 | 114 | 123 | -91 |
| 463 | 114 | 125 | -89 |
| 464 | 124 | 129 | -98 |
| 465 | 148 | 134 | -117 |
| 466 | 127 | 126 | -104 |
| 467 | 124 | 125 | -102 |
| 468 | 122 | 125 | -100 |
| 469 | 121 | 124 | -99 |
| 470 | 120 | 123 | -100 |
| 471 | 123 | 129 | -101 |
| 472 | 137 | 129 | -107 |
| 473 | 127 | 133 | -117 |
| 474 | 130 | 127 | -107 |
| 475 | 128 | 128 | -104 |
| 476 | 126 | 127 | -102 |
| 477 | 125 | 127 | -102 |
| 478 | 125 | 128 | -101 |
| 479 | 127 | 129 | -100 |
| 480 | 115 | 128 | -103 |
| 481 | 136 | 134 | -122 |
| 482 | 150 | 135 | -132 |
| 483 | 143 | 128 | -119 |
| 484 | 133 | 127 | -112 |
| 485 | 130 | 128 | -110 |
| 486 | 128 | 128 | -108 |
| 487 | 127 | 128 | -107 |
| 488 | 126 | 128 | -106 |
| 489 | 124 | 129 | -106 |
| 490 | 128 | 130 | -121 |
| 491 | 137 | 130 | -118 |
| 492 | 138 | 134 | -114 |
| 493 | 135 | 132 | -113 |
| 494 | 132 | 132 | -111 |

| | | | |
|---|---|---|---|
| 495 | 148 | 141 | -134 |
| 496 | 159 | 140 | -131 |
| 497 | 146 | 137 | -115 |
| 498 | 141 | 136 | -113 |
| 499 | 139 | 136 | -112 |
| 500 | 137 | 136 | -111 |
| 501 | 135 | 136 | -110 |
| 502 | 134 | 136 | -110 |
| 503 | 133 | 135 | -109 |
| 504 | 132 | 135 | -108 |
| 505 | 132 | 135 | -108 |
| 506 | 132 | 135 | -107 |
| 507 | 131 | 135 | -107 |
| 508 | 134 | 136 | -108 |
| 509 | 131 | 134 | -115 |
| 510 | 141 | 136 | -113 |
| 511 | 150 | 151 | -127 |
| 512 | 143 | 138 | -113 |
| 513 | 131 | 131 | -102 |
| 514 | 133 | 134 | -104 |
| 515 | 132 | 134 | -104 |
| 516 | 131 | 134 | -104 |
| 517 | 130 | 134 | -104 |
| 518 | 133 | 136 | -106 |
| 519 | 132 | 135 | -104 |
| 520 | 135 | 141 | -106 |
| 521 | 130 | 138 | -101 |
| 522 | 138 | 142 | -109 |
| 523 | 142 | 141 | -130 |
| 524 | 142 | 138 | -126 |
| 525 | 149 | 139 | -117 |
| 526 | 134 | 136 | -107 |
| 527 | 131 | 136 | -106 |
| 528 | 129 | 136 | -104 |
| 529 | 128 | 135 | -103 |
| 530 | 127 | 136 | -103 |
| 531 | 132 | 137 | -104 |
| 532 | 128 | 140 | -101 |
| 533 | 167 | 125 | -95 |
| 534 | 92 | 123 | -81 |
| 535 | 85 | 122 | -81 |
| 536 | 84 | 122 | -81 |
| 537 | 84 | 122 | -80 |
| 538 | 84 | 122 | -80 |
| 539 | 84 | 122 | -79 |
| 540 | 82 | 121 | -79 |
| 541 | 84 | 124 | -79 |
| 542 | 86 | 120 | -79 |
| 543 | 74 | 121 | -67 |
| 544 | 71 | 122 | -83 |
| 545 | 72 | 121 | -67 |
| 546 | 69 | 117 | -67 |
| 547 | 70 | 121 | -66 |
| 548 | 71 | 122 | -68 |

| | | | |
|---|---|---|---|
| 549 | 76 | 119 | -78 |
| 550 | 73 | 119 | -66 |
| 551 | 72 | 122 | -67 |
| 552 | 71 | 122 | -69 |
| 553 | 71 | 122 | -69 |
| 554 | 71 | 122 | -68 |
| 555 | 73 | 122 | -68 |
| 556 | 72 | 122 | -69 |
| 557 | 73 | 123 | -69 |
| 558 | 75 | 122 | -70 |
| 559 | 74 | 122 | -70 |
| 560 | 73 | 124 | -69 |
| 561 | 73 | 123 | -71 |
| 562 | 75 | 122 | -69 |
| 563 | 70 | 122 | -69 |
| 564 | 70 | 121 | -68 |
| 565 | 81 | 122 | -89 |
| 566 | 69 | 121 | -67 |
| 567 | 74 | 122 | -68 |
| 568 | 71 | 122 | -66 |
| 569 | 69 | 121 | -68 |
| 570 | 74 | 121 | -72 |
| 571 | 73 | 118 | -67 |
| 572 | 63 | 117 | -66 |
| 573 | 70 | 128 | -57 |
| 574 | 56 | 119 | -43 |
| 575 | 68 | 124 | -51 |
| 576 | 62 | 121 | -51 |
| 577 | 62 | 121 | -52 |
| 578 | 66 | 142 | -57 |
| 579 | 60 | 149 | -55 |
| 580 | 59 | 137 | -52 |
| 581 | 58 | 140 | -52 |
| 582 | 63 | 137 | -52 |
| 583 | 56 | 138 | -52 |
| 584 | 56 | 134 | -57 |
| 585 | 53 | 139 | -45 |
| 586 | 57 | 139 | -46 |
| 587 | 57 | 139 | -47 |
| 588 | 57 | 139 | -47 |
| 589 | 54 | 137 | -48 |
| 590 | 56 | 138 | -46 |
| 591 | 56 | 139 | -47 |
| 592 | 57 | 138 | -46 |
| 593 | 57 | 138 | -45 |
| 594 | 57 | 138 | -45 |
| 595 | 58 | 138 | -45 |
| 596 | 58 | 138 | -45 |
| 597 | 58 | 138 | -44 |
| 598 | 55 | 141 | -40 |
| 599 | 57 | 135 | -34 |
| 600 | 58 | 135 | -32 |

# 9.5 *Complete Raw Data for Cadaver 4*

## *9.5.1 Mid-Palatal Suture Sensor*

| time | 1 | 2 | 3 |
|---|---|---|---|
| 1 | 7 | 13 | 4 |
| 2 | 7 | 12 | 4 |
| 3 | 8 | 7 | 4 |
| 4 | 6 | 4 | 3 |
| 5 | 13 | 5 | 3 |
| 6 | 5 | -2 | 13 |
| 7 | 3 | -6 | 8 |
| 8 | 6 | -5 | 7 |
| 9 | 6 | -4 | 6 |
| 10 | 5 | -13 | 6 |
| 11 | 6 | -13 | 8 |
| 12 | 8 | -12 | 8 |
| 13 | 8 | -14 | 8 |
| 14 | 8 | -16 | 9 |
| 15 | 9 | -18 | 8 |
| 16 | 0 | -30 | 9 |
| 17 | 12 | -24 | 8 |
| 18 | -2 | -38 | 7 |
| 19 | 7 | -34 | 8 |
| 20 | 9 | -39 | 8 |
| 21 | 11 | -34 | 5 |
| 22 | 14 | -40 | 6 |
| 23 | 9 | -29 | 12 |
| 24 | 9 | -12 | 12 |
| 25 | 10 | 7 | 12 |
| 26 | 9 | 29 | 12 |
| 27 | 11 | 45 | 11 |
| 28 | 10 | 57 | 12 |
| 29 | 10 | 63 | 11 |
| 30 | 9 | 72 | 12 |
| 31 | 11 | 72 | 11 |
| 32 | 11 | 73 | 11 |
| 33 | 11 | 69 | 11 |
| 34 | 11 | 66 | 12 |
| 35 | 11 | 58 | 12 |
| 36 | 11 | 51 | 12 |
| 37 | 12 | 45 | 11 |
| 38 | 12 | 38 | 13 |
| 39 | 11 | 33 | 12 |
| 40 | 11 | 35 | 12 |
| 41 | 0 | 39 | 9 |
| 42 | 13 | 57 | 14 |
| 43 | 16 | 78 | 18 |
| 44 | 13 | 84 | 15 |
| 45 | 13 | 94 | 15 |
| 46 | 14 | 108 | 14 |
| 47 | 14 | 118 | 15 |
| 48 | 14 | 121 | 16 |
| 49 | 14 | 132 | 15 |
| 50 | 14 | 137 | 16 |
| 51 | 15 | 141 | 16 |
| 52 | 15 | 143 | 16 |
| 53 | 15 | 142 | 18 |
| 54 | 15 | 142 | 16 |
| 55 | 15 | 143 | 16 |
| 56 | 15 | 148 | 17 |
| 57 | 15 | 147 | 17 |
| 58 | 15 | 143 | 17 |
| 59 | 16 | 142 | 17 |
| 60 | 16 | 147 | 17 |
| 61 | 16 | 149 | 18 |
| 62 | 16 | 153 | 18 |
| 63 | 16 | 156 | 18 |
| 64 | 16 | 164 | 18 |
| 65 | 16 | 170 | 18 |
| 66 | 16 | 175 | 18 |
| 67 | 17 | 178 | 18 |
| 68 | 17 | 182 | 18 |
| 69 | 17 | 181 | 19 |
| 70 | 17 | 180 | 19 |
| 71 | 17 | 176 | 19 |
| 72 | 17 | 180 | 19 |
| 73 | 18 | 178 | 19 |
| 74 | 18 | 172 | 19 |
| 75 | 18 | 167 | 20 |
| 76 | 18 | 164 | 20 |
| 77 | 18 | 164 | 20 |
| 78 | 19 | 157 | 20 |
| 79 | 18 | 148 | 20 |
| 80 | 19 | 144 | 20 |
| 81 | 19 | 147 | 20 |
| 82 | 13 | 139 | 19 |
| 83 | -12 | 127 | 19 |
| 84 | -12 | 140 | 27 |
| 85 | 17 | 158 | 20 |
| 86 | 20 | 161 | 21 |
| 87 | 13 | 149 | 17 |
| 88 | 16 | 141 | 19 |
| 89 | 20 | 133 | 25 |
| 90 | 20 | 124 | 21 |
| 91 | 5 | 107 | 24 |
| 92 | 7 | 98 | 15 |
| 93 | 23 | 91 | 13 |
| 94 | 18 | 84 | 21 |
| 95 | 11 | 74 | 20 |
| 96 | 22 | 74 | 20 |
| 97 | 34 | 77 | 11 |
| 98 | 29 | 59 | 16 |
| 99 | 12 | -25 | 17 |
| 100 | 22 | -91 | 20 |
| 101 | 8 | -142 | 21 |
| 102 | 5 | -191 | 18 |
| 103 | 30 | -217 | 10 |
| 104 | 26 | -237 | 17 |
| 105 | 21 | -245 | 19 |
| 106 | 19 | -271 | 16 |
| 107 | 30 | -264 | 10 |
| 108 | 29 | -238 | 14 |
| 109 | 30 | -196 | 15 |
| 110 | 31 | -180 | 16 |
| 111 | 30 | -177 | 16 |
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| 113 | 47 | -158 | 7 |
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| 115 | 33 | -130 | 10 |
| 116 | 32 | -126 | 15 |
| 117 | 35 | -114 | 14 |
| 118 | 36 | -120 | 16 |
| 119 | 38 | -113 | 14 |
| 120 | 36 | -116 | 19 |
| 121 | 35 | -131 | 4 |
| 122 | 43 | -134 | 8 |
| 123 | 32 | -151 | 9 |
| 124 | 44 | -192 | 0 |
| 125 | 47 | -218 | 4 |
| 126 | 44 | -234 | 9 |
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| 132 | 54 | -215 | -5 |
| 133 | 41 | -205 | 4 |
| 134 | 60 | -196 | -5 |
| 135 | 58 | -201 | -10 |
| 136 | 56 | -198 | -4 |
| 137 | 50 | -192 | -2 |
| 138 | 113 | -161 | -24 |
| 139 | 104 | -147 | -12 |
| 140 | 95 | -138 | 5 |
| 141 | 99 | -133 | -9 |
| 142 | 81 | -117 | -8 |
| 143 | 98 | -101 | -6 |
| 144 | 80 | -97 | -1 |
| 145 | 94 | -85 | -5 |
| 146 | 74 | -82 | 12 |
| 147 | 71 | -82 | 7 |
| 148 | 75 | -70 | 9 |
| 149 | 120 | -55 | -22 |
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| 158 | 96 | -25 | -5 |
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| 164 | 119 | -63 | -23 |
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| 187 | 133 | 43 | -34 |
| 188 | 133 | 53 | -31 |
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| 246 | 141 | 196 | -16 |
| 247 | 165 | 210 | -32 |
| 248 | 163 | 211 | -26 |
| 249 | 159 | 213 | -29 |
| 250 | 174 | 223 | -32 |
| 251 | 176 | 219 | -33 |
| 252 | 174 | 221 | -32 |
| 253 | 173 | 223 | -32 |
| 254 | 173 | 227 | -31 |
| 255 | 173 | 234 | -30 |
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| 258 | 172 | 246 | -29 |
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| 263 | 180 | 253 | -34 |
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| 265 | 157 | 260 | -28 |
| 266 | 146 | 257 | -7 |
| 267 | 179 | 275 | -34 |
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| 270 | 174 | 285 | -24 |
| 271 | 174 | 283 | -36 |
| 272 | 176 | 284 | -35 |
| 273 | 176 | 287 | -34 |
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| 294 | 181 | 320 | -34 |
| 295 | 180 | 321 | -31 |
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| 297 | 187 | 311 | -29 |
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| 301 | 178 | 321 | -32 |
| 302 | 195 | 326 | -32 |
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| 308 | 187 | 325 | -34 |

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|---|---|---|---|
| 309 | 211 | 333 | -47 |
| 310 | 200 | 333 | -43 |
| 311 | 199 | 334 | -42 |
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| 313 | 198 | 336 | -40 |
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| 315 | 197 | 338 | -40 |
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| 322 | 195 | 367 | -34 |
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| 324 | 189 | 366 | -29 |
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| 334 | 201 | 387 | -36 |
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| 340 | 201 | 398 | -35 |
| 341 | 199 | 400 | -32 |
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| 343 | 191 | 395 | -26 |
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| 346 | 167 | 393 | -19 |
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## *9.5.2 Intermaxillary Suture Sensor*

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| 5 | 1 | 1 | 0 |
| 6 | 0 | 2 | 0 |
| 7 | 3 | 4 | 0 |
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| 9 | 3 | 36 | 13 |
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| 12 | 3 | 5 | 1 |
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| 18 | 6 | 2 | 1 |
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| 21 | 7 | 4 | 1 |
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| 23 | 6 | 4 | 2 |
| 24 | 6 | 4 | 2 |
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| 26 | 8 | 5 | 2 |
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| 35 | 6 | 3 | 3 |
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| 39 | 8 | 18 | 9 |
| 40 | 9 | 4 | 5 |
| 41 | 7 | 4 | 5 |
| 42 | 9 | 4 | 5 |
| 43 | 10 | 10 | 7 |
| 44 | 11 | 6 | 6 |
| 45 | 10 | 9 | 6 |
| 46 | 8 | 22 | 15 |
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| 49 | 10 | 6 | 7 |
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| 51 | 7 | 16 | 13 |
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| 53 | 9 | 6 | 7 |
| 54 | 10 | 8 | 8 |
| 55 | 8 | 13 | 10 |
| 56 | 8 | 16 | 11 |
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| 58 | 7 | 11 | 9 |
| 59 | 5 | 14 | 12 |
| 60 | 9 | 8 | 7 |
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| 85 | 10 | 18 | 15 |
| 86 | 11 | 18 | 16 |
| 87 | 13 | 26 | 18 |
| 88 | 11 | 31 | 18 |
| 89 | 10 | 37 | 21 |
| 90 | 9 | 27 | 20 |
| 91 | 11 | 27 | 20 |
| 92 | 11 | 30 | 22 |
| 93 | 7 | 48 | 29 |
| 94 | 4 | 46 | 29 |
| 95 | 8 | 36 | 26 |
| 96 | 9 | 42 | 27 |
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| 98 | 7 | 55 | 34 |
| 99 | 9 | 48 | 30 |
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| 108 | 7 | 93 | 56 |
| 109 | 8 | 87 | 52 |
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| 121 | 10 | 111 | 66 |
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| 123 | 9 | 122 | 69 |
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| 133 | 12 | 98 | 55 |
| 134 | 11 | 95 | 54 |
| 135 | 10 | 92 | 53 |
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| 163 | 13 | 80 | 35 |
| 164 | 12 | 78 | 34 |
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| 180 | 13 | 67 | 22 |
| 181 | 13 | 66 | 21 |
| 182 | 14 | 66 | 20 |
| 183 | 13 | 69 | 20 |
| 184 | 14 | 69 | 18 |
| 185 | 13 | 67 | 17 |
| 186 | 13 | 72 | 17 |
| 187 | 13 | 72 | 17 |
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| 189 | 15 | 70 | 16 |
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| 192 | 12 | 66 | 13 |
| 193 | 17 | 106 | 18 |
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| 197 | 17 | 150 | 35 |
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| 208 | 14 | 87 | 13 |
| 209 | 15 | 86 | 12 |
| 210 | 13 | 131 | 22 |
| 211 | 16 | 170 | 32 |
| 212 | 19 | 161 | 27 |
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| 225 | 17 | 129 | 17 |
| 226 | 15 | 164 | 19 |
| 227 | 15 | 165 | 25 |
| 228 | 14 | 155 | 21 |
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| 231 | 14 | 139 | 16 |
| 232 | 12 | 145 | 19 |
| 233 | 14 | 118 | 13 |
| 234 | 11 | 128 | 13 |
| 235 | 16 | 126 | 10 |
| 236 | 13 | 127 | 8 |
| 237 | 15 | 136 | 6 |
| 238 | 11 | 103 | 4 |
| 239 | 13 | 108 | 1 |
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| 241 | 14 | 116 | -1 |
| 242 | 12 | 98 | -4 |
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| 251 | 17 | 87 | -21 |

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| 258 | 15 | 132 | -7 |
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| 274 | 16 | 188 | -9 |
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| 277 | 15 | 143 | -12 |
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| 298 | 17 | 135 | -27 |

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| 357 | 14 | 102 | -23 |
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| 361 | 19 | 121 | -26 |
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| 365 | 15 | 122 | -28 |
| 366 | 18 | 161 | -28 |
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| 368 | 20 | 147 | -36 |
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| 371 | 18 | 131 | -34 |
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| 377 | 25 | 164 | -39 |
| 378 | 27 | 165 | -43 |
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| 380 | 17 | 136 | -31 |
| 381 | 16 | 121 | -32 |
| 382 | 17 | 131 | -29 |
| 383 | 19 | 126 | -31 |
| 384 | 18 | 124 | -31 |
| 385 | 19 | 126 | -32 |
| 386 | 19 | 127 | -31 |
| 387 | 19 | 124 | -34 |
| 388 | 19 | 123 | -35 |
| 389 | 19 | 122 | -35 |
| 390 | 18 | 121 | -36 |
| 391 | 18 | 121 | -36 |
| 392 | 19 | 120 | -38 |

## *9.6 Journal Manuscript for The Angle Orthodontist*


### Abstract

**Quantification of Forces Dissipated Through Bone When Using Rapid Maxillary Expansion**

OBJECTIVE: To quantify the forces dissipated through bone when using rapid maxillary expansion in a cadaveric model.

MATERIAL AND METHODS: Stress-strain gauges were bonded to bone of human adult cadavers adjacent to the mid-palatal and intermaxillary sutures using a cyanoacrylate adhesive. The gauges were used to record the forces exerted on the craniofacial complex using a modified RME. Values generated were converted to force in grams.

RESULTS: Complete activation of the modified RPE appliance yielded a mean maximum force value for the mid-palatal suture of 986.58 grams (±203.72), while the intermaxillary suture was 759.99 grams (±143.77). A statistically significant difference in force values between the mid-palatal and intermaxillary sensor sites was found ($p<0.05$). No specimens were found to have either the mid-palatal or intermaxillary suture become patent following activation. The difference in values at the different anatomic locations could indicate that the force generated by the RME becomes dissipated by the hard and soft tissues in the craniofacial complex and that the further away from the RME, the lower the value. This may further support the theory that piezoelectricity mediates alveolar remodelling by orthopaedic appliances or that cell signalling at the cellular level responds to dissipated forces to trigger the osseous response.

CONCLUSIONS: Forces generated by RME devices were dissipated through the bone at levels that exceed orthopaedic force range. The further from the site of force delivery, the lower the values, suggesting dissipation involves many factors including hard and soft tissue which can absorb forces thereby decreasing their magnitude.

## INTRODUCTION:

Rapid maxillary expanders (RMEs) are widely used orthopaedic appliances in orthodontics and have existed for over 100 years[1]. Since then, a plethora of orthopaedic devices have been established, all having the goal of modifying or altering growth of the craniofacial complex[2,3]. These include headgears, functional appliances and RMEs. RMEs work by exerting forces on the teeth and bone that are dissipated throughout the craniofacial complex resulting in anatomical changes involving bone remodelling. Although the literature describes the anatomic areas to which this force is dissipated[4], no investigation has quantified the force on bone at the applied areas and its dissipation throughout the craniofacial complex.

The evidence in the literature describing the clinical efficacy of orthopaedic appliances is exhaustive. It is believed that exogenous forces produced by these appliances result in sutural bone strain that causes a cellular response in growth[5] Orthopaedic loading on the dentition results in the transmission of these forces to produce tensile and compressive strain on the facial and cranial sutures that absorb and transmit these forces. Sutures absorb these stresses and their bony edges are displaced, either through tension or compression. This results in modulating sutural growth at the cellular level resulting in overall growth modification[5]. Further, different sutures have different responses to force. This force exerts a strain on the sutures of the craniofacial complex resulting in microscopic changes that over time summate to result in macroscopic effects.

Isaacson and others[6] used strain gauges cemented to RMEs in patients and found that a single activation of the expansion screw of 0.2mm (one quarter revolution) produced approximately 1.3-4.5 kg (3-10 pounds) of force. The force decayed rapidly initially and then continued to slowly decrease. Isaacson found that the resistance of the expansion was not from the mid-palatal suture but from the bones that articulated the maxilla because there was not a significant change in the force once the sutures opened. He found that a smaller force was required for younger patients versus older patients due to less resistance to expansion of the palate. In a similar study, Zimring and Isaacson[7] determined that it was the facial skeleton that was the main resistance to expansion. The maximum loads on patients ranged from 7.5-15.7 kg of force during treatment and these forces gradually dissipated during the six week retention period.

In a photoelastic study of the human skull, Chocanos and Caputo[4] measured stresses using RME of the Haas, Minne-expander, Hyrax, and quad helix types. Each of the appliances produced different stresses transmitted through the bones of the craniofacial complex and effects on the various sutures. Fixed appliances produced stress that was concentrated in the anterior region of the palate that progressed posteriorly toward the palatine bone. The Haas, Minne-expander, and Hyrax appliances resulted in stresses that were in the orthopedic range. The stress was concentrated in the anterior region of the palate and progressed to the posterior and radiated to areas superiorly along the perpendicular plates of the palatine bone deeper to anatomic structures such as the lacrimal, nasal, and malar bones, the pterygoid plates of the sphenoid, the zygomatic process and the medial wall of the orbit. Interestingly, increased activation decreased retention resulting in less of a stress produced at these areas. Furthermore, with increased activation, the palate began to separate. The appliance was found to primarily affect posterior teeth. In a finite element analysis study, Jafari and others[8] demonstrated that the pterygoid plates are bent more than 2mm during rapid palatal expansion.

Understanding the complex interplay of sutural growth may be the key to understanding the mechanism of action of orthopaedic loading and elucidating a more ideal force to utilize with orthopaedic appliances. This ideal, is the minimum mechanical force that results in the maximum desirable skeletal modification in the shortest period of time.

The current study quantifies the force and assesses the dissipation of the force exerted by an RME at the intermaxillary and mid-palatal sutures on adult cadavers with stress/strain gauges. This exact magnitude of forces may help in better understanding the mechanisms of how sutural growth is affected.

## MATERIALS AND METHODS

A stock alginate tray (Ortho Organizers, U.S.A.) was modified by cutting it into 2 equal halves and joined in the center by a 12mm jack-screw (Forestadent, Pforzheim, Germany) soldered to each half with an anterior and posterior contact point (Figure 1). Permission was obtained from the Head o the Department of Anatomy, Faculty of Medicine to perform this study. Human cadavers were selected from the school's Gross Anatomy Laboratory at random and had at least molars and premolars present to allow for better, natural retention of the fabricated RME appliance. In total, 4 suitable cadavers (2 male and 2 female) were used in the study ranging from 68 to 79 years old (mean of 73 years old). Careful dissection of the cadaver was performed in the palatal and intermaxillary area. In the palatal area, an incision was made through the keratinized gingival tissue of the palate. This incision followed the line of the teeth and/or the residual alveolar ridge from the posterior aspect of the second molar to the midline. A flap was then raised exposing the underlying bone. For the intermaxillary area, an incision was made to cut the gingival tissue in the maxillary anterior area. This incision followed the line of the maxillary anterior teeth and/or the residual alveolar ridge from the area of the first premolar to the midline. A flap was then raised using to expose the underlying bone. The exposed bone was then cleaned thoroughly with gauze dipped in a 99.9% pure ethanol solution for 5 minutes. Next, dry gauze was used to remove any and all moisture from the respective areas for another 5 minutes. A rosette strain gauge sensor (Figure 2) equipped with 6, 10 foot leads (catalogue number C2A-06-062LR-350 (Intertechnologies), was then cemented to the dried bone using MBond200 (Intertechnologies), a cyanoacrylate bonding adhesive. With firm finger pressure, the sensor was placed in position and held for 1 minute to allow the adhesive to dry and ultimately bond to the bone. For the palatal suture, the sensor was placed 2mm to the right of the mid-palatal suture and midway between the anterior segment and the junction of the palatal process of the maxillary bone/palatine bone. The orientation of the sensor was such that the leads faced posteriorly or towards the cadaver's throat. For the intermaxillary suture, the sensor was placed 2mm to the right of the intermaxillary suture and 5mm gingival to the highest point of bone from the tooth or residual alveolar ridge. The orientation of the sensor was such that the leads faced inferiorly or towards the cadaver's throat. All leads were then connected to the P3 measuring device (Intertechnology, Canada) prior to RME placement. Kerr brown dental compound (GAC Dentsply, USA) was placed in a water bath and heated to 60 °C. The compound was then placed and moulded into the modified RME device and placed immediately into the oral cavity of the cadaver. Once the compound cooled and hardened the RME device was continually activated every 5-10 seconds until it could not be turned any further, for a total of 48 turns or 12 mm. Results were stored directly on the P3 device on a SD memory card and accessed via personal computer into a spreadsheet format. Data obtained was then put through a complex mathematical macro developed by Intertechnology Canada to convert the μstrain value and incorporate the multi-directional axes of the rosette strain gauge into a useable format (force in grams). A two-tailed, paired Student t-test was used to compare the maximum and minimum force values at the different sites for statistical significance between sites and cadavers.

## RESULTS

### *Mid-Palatal Suture Comparisons*

There are generally 4 distinct patterns present for each cadaver (Figure 3-6). The first phase can be described as a gradual increase in force values, followed by a second phase involving a more steep or logarithmic increase in force values. The third phase corresponds with a levelling-off followed by the fourth and final phase of a slight decline from the initial levelling-off. Cadaver 4 produced the lowest force values while Cadaver 2, the highest (Table 1). The mean maximum force value obtained for the mid-palatal suture was 986.58 grams (±203.72). Another interesting observation is that Cadavers 2, 3 and 4 (Figure 4, 5, 6) appear to follow the same logarithmic trend in increasing force levels in the second phase of RME activation. Although Cadaver 1 (Figure 3) also shows an increase, it is more gradual as compared to the others. Finally it is apparent that the experiment on Cadaver 1 was the longest test to perform, while Cadaver 4 was the shortest. The display of distinct spikes in the graph occurred at each activation followed by a period of gradual relaxation and corresponding drop in the force value over time. The spikes that corresponded to activations ranged from 100-300 grams of force.

***Intermaxillary Suture Comparisons***

The intermaxillary sensor site showed a similar trend as the mid-palatal site, however at different time intervals when compared to the palatal suture site and also lower force values. It is apparent that Cadaver 4 produced the lowest force values while Cadaver 1, the highest (Table 2). The mean maximum force value obtained for the intermaxillary suture site was 759.99 grams (±143.77). Although all cadavers appear distinctly different, it appears that aside from Cadaver 3, the rest appear to follow the same logarithmic trend in increasing force levels in the second phase of RME activation. Finally it is apparent that the Cadaver 1 experiment was the longest test to perform, while Cadaver 4 was the shortest. It is interesting to note that Cadaver 3 (Figure 5) displayed a sudden drop in force values at approximately 451 seconds. The display of distinct spikes in the graph occurred at each activation followed by a period of gradual relaxation and corresponding drop in the force value over time. The spikes that corresponded to activations ranged from 50-350 grams of force.

Maximum force values of all cadavers were compared for statistical significant differences using a two-tailed, paired Student t-test. It was determined that there was a statistical significant difference of the maximum force values between the mid-palatal and intermaxillary sensor site ($p<0.05$).

**DISCUSSION**

Despite the extensive research of the effects of the RME appliance, this is the first study that measured the force exerted directly on bone in the human cadaver while activating an RME appliance.

Force values obtained for both the mid-palatal and intermaxillary sites exhibit values that were well within and above the estimated range of orthopaedic values (±500 grams). Although each cadaver provided specific values and force patterns, there appears to be a general trend of increasing force levels once the RME is activated. There were however detectable differences between cadavers, which are expected due to individual variation from specimen to specimen with varying degrees of bone density soft tissue thickness. Gender may also play a role, as the female cadavers were generally smaller than the male cadavers. Our sample was too small to determine gender differences and as there was no objective way to determine the hard and soft tissue thickness of each cadaver. In Cadaver 3, at approximately 450 seconds, the RME appliance slipped off the Cadaver's oral cavity producing the jump as displayed in Figure 5. In Cadaver 4, some teeth fractured as the expansion was taking place, and as a result, the graph did not follow a gradual increase over time, especially during the first part of the expansion (Figure 6). It is not expected that in a living subject the same type of teeth fracture would occur, due to the elastic fibers in the living subjects, vitality of the PDL and blood supply.

When comparing the 2 sites of sensor placement specifically, it was noted the force levels at the mid-palatal sensor site produced significantly higher values than the intermaxillary sensor site. Since the force production was further away from the intermaxillary site, this is to be expected. During initial pilot testing, our study involved placement of more sensors at varying sites throughout the craniofacial complex. Those sensors that were placed further away from the RME device registered less force on the P3 measuring device, which confirms the findings of a similar study[6]. This gives credence to the theory that minute orthopaedic forces may have an indirect effect on changes in the craniofacial skeleton via biochemical and/or cellular stimulatory effects induced by dissipated forces. These effects potentially spawned by the dissipated forces and despite being barely measurable, could work at a distance away from the source of the force production.

According to Buckland-Wright[9], sutures can absorb a considerable amount of energy, which is what probably also occurred in our study. If this were not the case, the force levels would continue to increase with no relaxation or fall in the values as time progressed. Indeed, there were general trends of increases over time, but they levelled off in all of our trials suggesting that not only the sutures, but the surrounding hard and soft tissues may play a role in force dissipation across the craniofacial osseous and non-osseous regions.

All sutures were given a visual and tactile examination following complete activation with no sutures having demonstrated any disconnect from one another, or fracture, despite the 12 mm of activation of the RME appliance. A study by Wehrbein and Yildizhan[10] analyzed the sutures of 18-38 year-old cadavers and found fusion had not actually occurred but the cadavers in our study were much older and cannot be accurately compared as a result. Wehrbein and Yildizhan also demonstrated that different cadavers exhibited different degrees of suture obliteration. This was confirmed by Persson and Thilander in 1977 who even found a 54 year-old subject without ossification[11]. Furthermore, even if the mid-palatal suture were to break, it must be borne in mind that in elderly specimens there is additional resistance at the pterygomaxillary interface from the pterygoid plates of the sphenoid bones, which have a tendency to bend laterally and prevent the posterior area of the suture from opening[4, 8, 12].

With RME appliances, the opening of the suture generally follows a fan-shape pattern with a larger opening in the anterior area and less in the posterior. This may indicate a higher force value in the anterior area or less resistance to expansion. In the photoelastic study of Chaconas and Caputo[4], it was found that the stresses generated in the anterior region of the palate were higher and became less and less posteriorly. This was not the case in our study as the forces generated in the anterior area were significantly less than the posterior area ($P<0.05$). The explanation for this could be that Chaconas's study involved a plastic simulation of a human skull and did not factor in the effect of soft tissue which was taken into account in our study. Anatomy may play a role in the fan-shape expansion pattern as there are only soft tissue structures anteriorly and posteriorly more hard tissue structures present which can impede or lessen the effect of expansion. This probably accounts for the higher force generation in the palatal area. However, Chaconas et al[4] found that the forces generated were in fact orthopaedic in nature which was confirmed in our study. Regardless, it is considered appropriate to generate higher forces in older patients requiring RME so that the force can be used to achieve some orthopaedic change, as described by Isaacson (1964).

Isaacson et al[6] using strain gauges in RME's found that large forces of 1.3-4.5 kg were achieved from single activations with rapid initial decay. Zimring and Isaacson[7] found that these forces were even higher in a subsequent study (7.5-15.7 kg). Although our study did not produce values as high as these, it could be because Isaacson et al put the sensor directly on the RME, whereas our sensor was directly on the bone. This difference can therefore be postulated on the basis of the force which may have been dissipated through all surrounding structures, including hard and soft tissues.

Oberheim and Mao[13] found that bone strain was higher in younger skulls than in older skulls. Using this study as an example, it would be fair to assume that the forces generated in our study would result in even higher force values in younger patients due to their bone being less stiff than adult bone and subject to greater deformation. However, according to the finite element analysis study of Holberg et al[14], higher cranial base stresses were displayed due to the decrease in elasticity of the adult skull versus the young skull.

Our study also confirmed the findings of Timms'[15] which demonstrated the greatest stress in the area it is being delivered, while further away, it diminishes. In concert with these previous studies, our research confirms the theory of orthopaedic force decay and dissipation along the anatomic structures of the craniofacial complex.

## CONCLUSIONS

- Forces generated by RME devices are dissipated through the bone to the mid-palatal and intermaxillary sutures at levels that are consistent with the orthopaedic force range.
- Orthopaedic forces generated at both the mid-palatal and intermaxillary sutures do not result in suture patency in aged cadavers.
- The further away from the site of force delivery, the lower the recorded force values, suggesting forces dissipate and diminish as they are transferred along the hard tissue and possibly absorbed by the sutures and surrounding soft tissue.
- Despite the small magnitude of dissipated forces at distant sites, those forces may nevertheless be at levels sufficient to enable a cell signalling response at the cellular level thus generating a histobiochemical reaction and osteogenic response.

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**Figure Legends:**

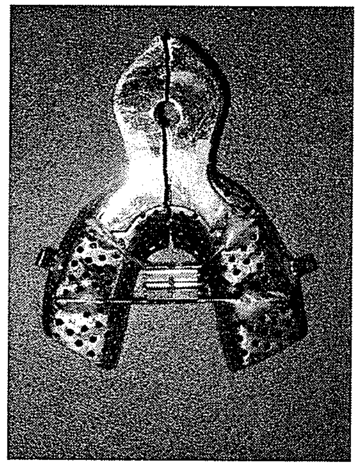

**Figure 1: 12mm hyrax expansion screw soldered to a sectioned impression tray**

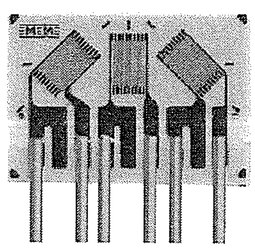

**Figure 2: A rosette strain gauge sensor equipped with 6, 10 foot leads (catalogue number C2A-06-062LR-350 (Intertechnologies))**

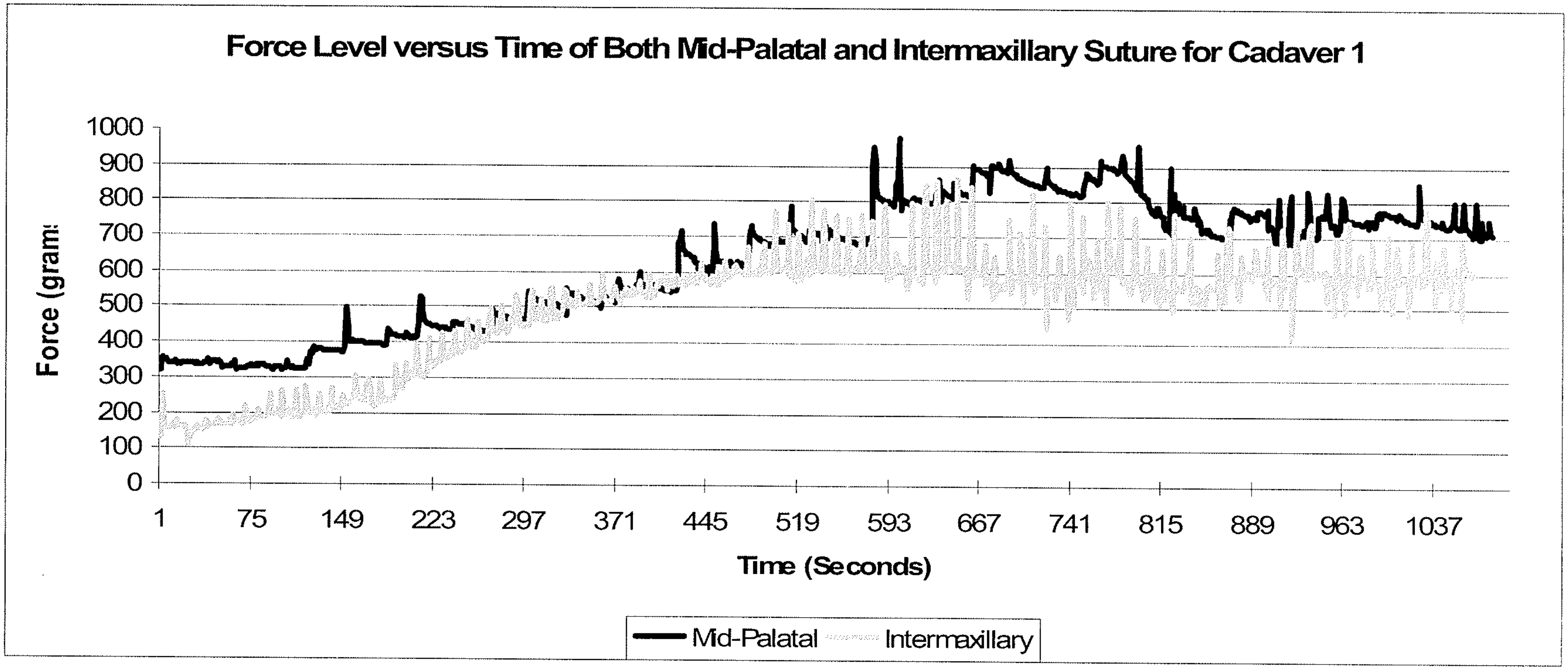


**Figure 3: Force level (grams) versus time (seconds) of both mid-palatal and intermaxillary suture for cadaver 1**

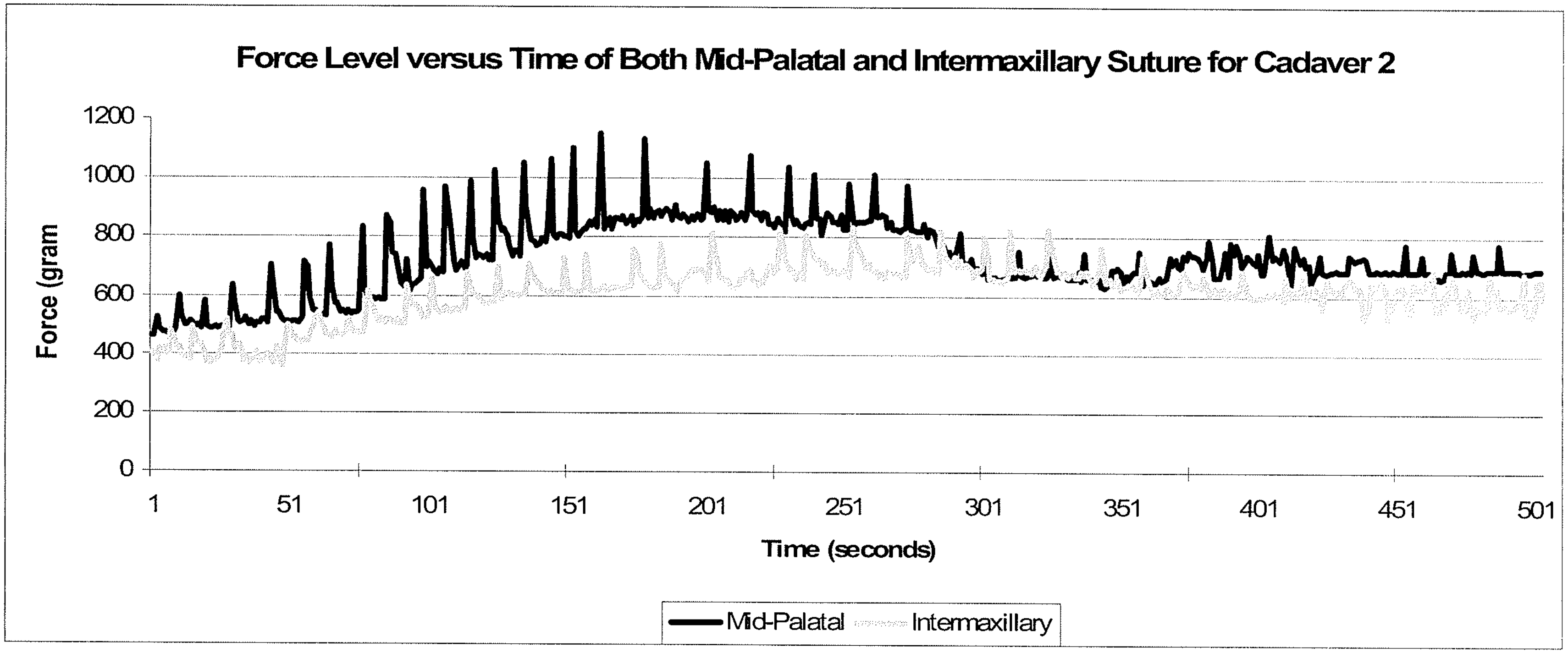


**Figure 4: Force level (grams) versus time (seconds) of both mid-palatal and intermaxillary suture for cadaver 2**

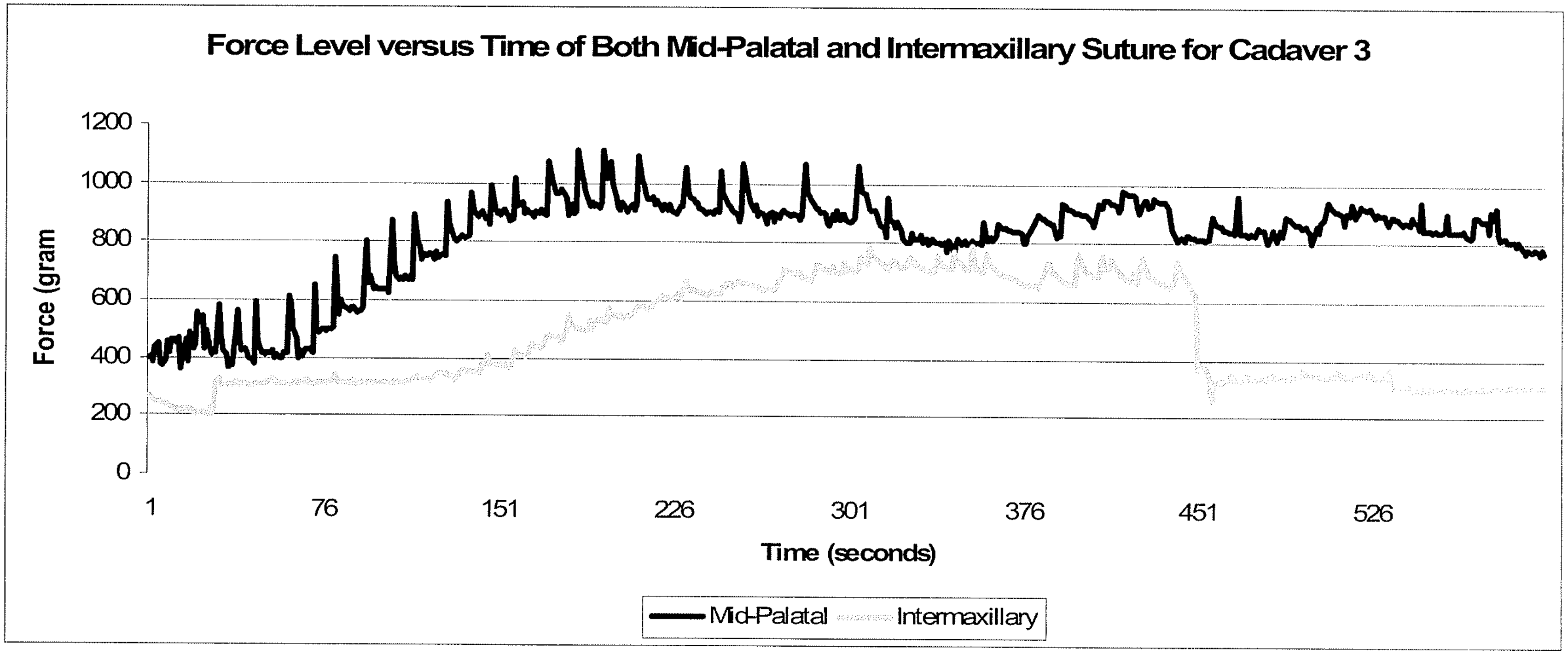


Figure 5: Force level (grams) versus time (seconds) of both mid-palatal and intermaxillary suture for cadaver 3

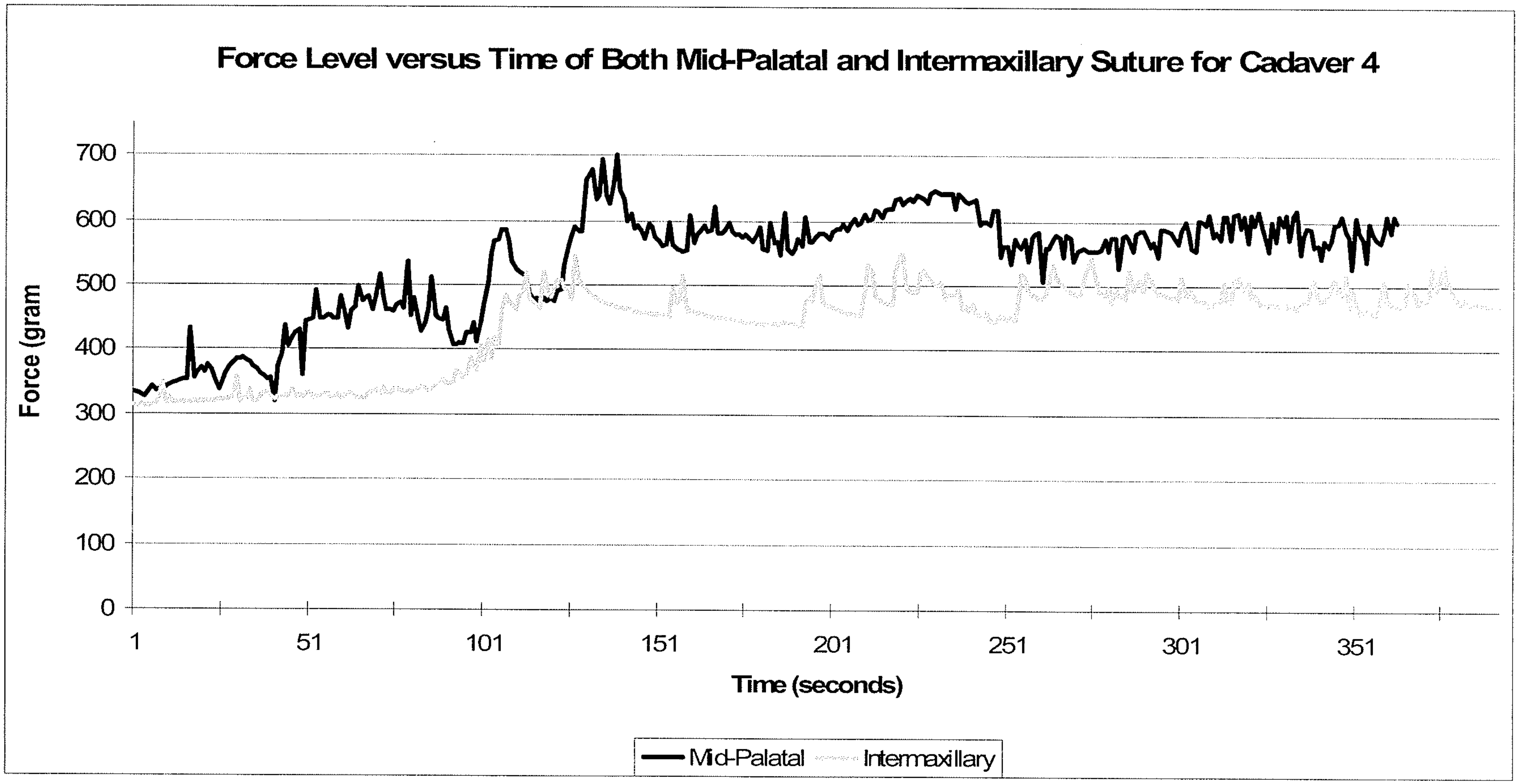


Figure 6: Force level (grams) versus time (seconds) of both mid-palatal and intermaxillary suture for cadaver 4

| | Maximum | Minimum | Difference |
|---|---|---|---|
| **Cadaver 1** | 980.27 | 319.18 | 661.09 |
| **Cadaver 2** | 1152.42 | 461.36 | 691.06 |
| **Cadaver 3** | 1112.05 | 361.46 | 750.59 |
| **Cadaver 4** | 701.59 | 319.44 | 382.15 |

**Table 1: Maximum and minimum force values (grams) of the mid-palatal sensor site for all cadavers**

| | Maximum | Minimum | Difference |
|---|---|---|---|
| **Cadaver 1** | 862.89 | 111.58 | 751.31 |
| **Cadaver 2** | 835.84 | 357.22 | 478.62 |
| **Cadaver 3** | 792.49 | 199.55 | 592.94 |
| **Cadaver 4** | 548.77 | 312.63 | 236.14 |

**Table 2: Maximum and minimum force values (grams) of the intermaxillary sensor site for all cadavers**