DEVELOPMENT OF A COMPUTER PROGRAM DEMONSTRATING THE ANATOMY OF THE EQUINE PARANASAL SINUSES

A Thesis

by

CATHERINE MARIE RUOFF

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

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May 2011

Major Subject: Biomedical Sciences

Development of a Compter Program Demonstrating the Anatomy of the Equine

Paranasal Sinuses

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ABSTRACT

Development of a Computer Program Demonstrating the Anatomy of the Equine Paranasal Sinuses. (May 2011)

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The equine paranasal sinuses are a frequent site of disease. They are anatomically complex structures encased in bone that are difficult to visualize. Because of their complexity and location, accurate diagnosis and treatment of the affected sinus(es) is difficult without a good understanding of their anatomy. Use of 3-D computer models in anatomy education has increased in recent years and shows promise in teaching anatomy of complex structures. The goal of this thesis was to develop a computer program illustrating a 3-D model of the equine paranasal sinuses to aid teaching the anatomy of the paranasal sinuses. A CT scan of a horse's head was performed and a 3-D reconstruction was generated. The paranasal sinuses were illustrated in the reconstructed images using Adobe Photoshop 6.0. Adobe Flash Professional CS5 was used to create an interactive computer program from the images. The resulting computer program depicts the sinuses and features of the skull at five key points plus or minus nine degrees of rotation.

NOMENCLATURE

CT	Computed Tomography
3-D	Three-dimensional
VR	Virtual Reality
PET/CT	Positron Emission Tomography/Computed Tomography
2-D	Two-dimensional
MRI	Magnetic Resonance Imaging

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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

ANATOMY OF THE EQUINE PARANASAL SINUSES

The paranasal sinuses are extensive air-filled diverticula of the nasal cavity. In the horse, there are six pair of sinuses: dorsal conchal, middle conchal, ventral conchal, maxillary (which is divided into rostral and caudal parts), frontal, and sphenopalatine.[1, 2] Some texts describe an ethmoidal sinus while others refer to the middle conchal sinus, which is within the greater ethmoturbinate.[3] For the remainder of this paper, the term middle conchal sinus will be used. The dorsal conchal, ventral conchal, frontal, and rostral and caudal maxillary sinuses are generally considered to be the most clinically significant sinuses.[3, 4] However, ethmoid hematomas and primary sinusitis may affect the middle conchal sinus. Although rare, disease of the sphenopalatine sinus may result in significant clinical signs as a result of the sphenopalatine sinus's close relationship with the brain, pituitary gland, and major blood vessels and cranial nerves.[2] The paranasal sinuses are lined by pseudostratified columnar ciliated epithelium with goblet cells[5]. The function of the paranasal sinuses is unknown, although the air-filled sinuses reduce the weight of the horse's head.[6]

This thesis follows the style of the Journal of Veterinary Medical Education.

Dorsal Conchal Sinus

The dorsal, middle, and ventral nasal conchae are thin bony scrolls consisting of basal lamellae that attach to the lateral aspect of the nasal cavity. Extending dorsally from the basal lamellae are spiral lamellae which form scrolls. The free border of the caudal part of a spiral lamella of each concha attaches to its basal lamellae or with a neighboring facial bone, enclosing the sinus of the same name.[5-7] A bony septum, the conchal septum,[6] located in a plane midway between the rostral margin of the orbit and the infraorbital foramen at the approximate level of the first maxillary molar divides the dorsal nasal concha into rostral and caudal parts. The rostral portion of the concha communicates with the nasal cavity directly. The caudal part of the dorsal nasal concha houses the extensive dorsal conchal sinus. The dorsal roof of the dorsal conchal sinus is the nasal bone.[1, 4, 7, 8] Radiographically, the rostral boundary of the dorsal conchal sinus may be visualized just dorsal to the first maxillary molar and ventral to the nasal bone. The dorsal conchal sinus is superimposed over the dorsal half of the nasal cavity on a lateral radiograph. Because the dorsal nasal meatus is very narrow, the dorsal conchal sinus nearly reaches the median plane resulting in superimposition over the nasal cavity on a ventrodorsal radiograph.[7]

There is an extensive communication between the dorsal conchal and frontal sinuses. As a result, the dorsal conchal and frontal sinuses are often referred to as the conchofrontal sinus. Secretions in the dorsal conchal sinus travel through the frontal sinus, the frontomaxillary opening, and caudal maxillary sinus to empty into the nasal cavity via the nasomaxillary opening.

Frontal Sinus

The neurocranium and the caudal part of the nasal cavity are covered by the frontal bone. The frontal bone is composed of external and internal plates which surround the frontal sinus, although the lacrimal and nasal bones also contribute to the dorsal boundary. The frontal sinus is caudodorsal to the nasal cavity. The left and right frontal sinuses are separated by a median bony septum, the septum sinuum frontalium. The frontal sinus extends laterally from the midline into the zygomatic process of the frontal bone. In the adult horse, the rostral limit of the frontal sinus is at the approximate level of the fifth maxillary cheek tooth (second molar). The caudal boundary of the frontal sinus is at a level just rostral to the temporomandibular joint. The floor of the frontal sinus is uneven as it covers the ethmoidal labyrinth. Multiple incomplete bony lamellae, lamellae intrasinuales, partially divide the frontal sinus. Unlike other species, the frontal sinus freely communicates with the dorsal conchal sinus rostromedially.[1, 4, 5, 8] The ethmoidal artery is the primary blood supply to the frontal sinus.[9]

There is a large oval communication between the frontal sinus and the caudal maxillary sinus, the frontomaxillary opening, which is located rostrolateral to the ethmoidal labyrinth at the level of the bony lacrimal canal. This opening allows for drainage of material from the conchofrontal sinus to the caudal maxillary sinus, which communicates with the nasal cavity via the nasomaxillary opening.[1, 4, 5, 8] There are several descriptions in the literature of the position of the frontomaxillary opening. *Rooney's Guide to the Dissection of the Horse* describes the opening as being between the medial canthus of the eye and the median plane.[8] A study describing endoscopy of the paranasal sinuses of 20 horses indicated the frontomaxillary opening is located in the lateral aspect of the floor of the frontal sinus approximately five cm lateral to the median plane.[10] A study on the communications between the nasal and paranasal sinuses in horses using computed tomography by Probst, et al. indicates that the position of the frontomaxillary opening varies with age. The opening is in a dorsal plane and extends from the rostral end of the third premolar 20-50 mm caudally to the level of the first molar in young horses, while in older horses, the opening extends from the level of the second molar to 20 mm caudal to the third molar. Additionally, the size of the communications between the sinuses was variable depending on the type of horse.[11]

Radiographically, overlying bone causes the frontal sinus to appear smaller than its anatomic boundaries indicate. The frontal sinus appears to be divided into two parts on a lateral radiograph. One part is dorsal and caudal to the ethmoid turbinates. It appears radiolucent because the frontal sinus is wide. The frontomaxillary opening is located in this caudal portion of the frontal sinus. The rostral portion of the frontal sinus may be visualized rostrodorsal to the ethmoid turbinates. Its cranial border may be visualized dorsal to the second molar and has a scalloped appearance radiographically.[7]

Maxillary Sinus

The maxillary sinus is the largest of the paranasal sinuses[1] and is located lateral to the nasal cavity.[7] Its bony boundaries are the maxilla, lacrimal, and zygomatic bones laterally and the maxilla, ventral nasal concha, infraorbital canal and a small portion of the ethmoidal labyrinth medially. A line drawn from the rostral end of the facial crest to the infraorbital foramen approximates the rostral extent of the maxillary sinus. The dorsal boundary can be approximated by a line extending caudally from the infraorbital foramen parallel to the facial crest. Ventrally, the sinus is bounded by an irregular portion of the maxilla composed of multiple thin bony plates, alveolar septa, that cover the roots of the maxillary cheek teeth.[1] Because the roots of several of the caudal cheek teeth project into the maxillary sinus, the size of the maxillary sinus varies depending on the age of the horse. The roots of the molars are found within the maxillary sinus. In foals, the rostral maxillary sinus is nearly completely filled by the roots of the cheek teeth. As the horse's teeth continually erupt and the roots become shorter, the maxillary sinus gradually enlarges[1, 12] and the rostral extent of the maxillary sinus is near the infraorbital foramen,[5] while the ventral extent of the sinus may be ventral to the facial crest.[13] Additionally, the teeth associated with the maxillary sinus vary with age. In the foal, only the fourth premolar and first molar are related to the sinus. As the horse ages, the fourth maxillary premolars and the first, second, and third maxillary molars are associated with the sinuses. Finally, in older horses, only the maxillary molars are associated with the maxillary sinus.[4] Branches of the sphenopalatine artery provide the major blood supply to the maxillary sinus.[9]

The maxillary sinus is divided into rostral and caudal parts by a thin complete obliquely oriented bony septum, the septum sinuum maxillarium,[1] that is a ventral continuation of the ventral conchal bulla.[14] The septum is somewhat variable in location and its usual location is variable between references. The lateral edge of the septum is usually about five cm caudal to the rostral end of the facial crest[1] and is usually seen dorsal to the first molar on a lateral radiograph if the x-ray beam is parallel to the septum.[7] Generally, the septum is located over the middle of the roots of the second maxillary molars.[3, 15] In a study of 20 horses, the septum was located dorsal to the roots of the second maxillary molar in 14 horses and between the first and second maxillary molars in six horses. In all 20 of the horses in this study, the roots of the first maxillary molar projected into the rostral maxillary sinus,[10] although Bertone mentions the first maxillary molar may be located in the caudal maxillary sinus in some horses.[16] In some horses, the septum may be located as far rostrally as the rostral end of the facial crest or as far caudally as the orbit. From its lateral edge, the septum extends dorsally and caudomedially. The dorsal portion of the septum is formed by the caudal end of the ventral nasal concha, so it is very thin and often cribriform. However, when covered on both sides by mucous membranes, the septum between the rostral and caudal maxillary sinuses is complete. Because the septum is complete, there is no communication between the rostral and caudal maxillary sinuses in the normal horse. One exception to this is the mule, in which the septum is often smaller or absent.[1] The septum may be partially or completely eroded in cases of chronic inflammation.[3, 16]

The rostral and caudal maxillary sinuses share a common opening into the middle nasal meatus, the nasomaxillary opening.[1] The nasomaxillary opening is the sole site of drainage into the nasal cavity for the paranasal sinuses. The septum sinuum maxillarium divides the nasomaxillary opening, preventing communication between the rostral and caudal maxillary sinuses in the normal horse.[7] The rostral and caudal maxillary sinuses each have a separate duct that carries secretions to the nasomaxillary opening.[3] The nasomaxillary opening is located dorsally making effective drainage of material from the maxillary sinuses difficult.[1, 7] The location of the nasomaxillary opening is variable between horses and references. In one study, the nasomaxillary opening was located at the level of the second and third molar,[11] while another study found its location to be variable between horses, and was located between the fourth premolar and the first molar. The boundaries of the opening into the nasomaxillary opening from the caudal maxillary sinus are the ventral conchal bulla ventrally, the maxilla laterally, the floor of the dorsal conchal sinus dorsally, and the medial wall of the ventral conchal sinus medially. The opening from the rostral maxillary sinus into the nasomaxillary opening is against the maxilla laterally. The dorsoventral extent of the nasomaxillary opening is less than two mm, although it may be smaller in the live horse as a result of the venous plexus in the mucosa. As a horse's age increases, the medial to lateral width of the nasomaxillary opening also increases.[14] The nasomaxillary opening is not seen radiographically.[7] However, the nasomaxillary opening's entrance into the rostral maxillary sinus was found medial to the nasolacrimal canal in a study of 10 horses. The position of the nasomaxillary opening may be estimated by the locations of the nasolacrimal canal, the fourth premolar, and first molar.[14]

The rostral maxillary sinus communicates with the ventral conchal sinus via the conchomaxillary opening over the infraorbital canal which is attached to the alveolar bone covering the roots of the cheek teeth by bone.[1, 4, 8, 12] The conchomaxillary opening is wide and is located at the level of the rostral end of the second molar to the middle of the third molar.[11] In many horses, the rostral wall of the maxillary sinus is formed by the roots of the fourth premolar.[12] As a result, the rostral boundary is generally seen dorsal to the roots of the fourth maxillary premolars on a lateral radiograph, although this may vary depending on the age of the horse. It may not be visible in young horses because of overlap of tooth roots.[7]

The caudal maxillary sinus is the larger of the two parts of the maxillary sinus. It communicates medially with the sphenopalatine sinus over the infraorbital canal.[1, 4, 8] It also communicates with the middle nasal concha medially. The caudal maxillary sinus communicates with the frontal sinus dorsally via the frontomaxillary opening.[1] Radiographically, the rostral boundary is approximately at the level of the rostral end of the facial crest and dorsal to the first molar. The caudal limit is difficult to identify radiographically because the opening into the sphenopalatine sinus, overlying teeth, ethmoid turbinates, and vertical ramus of the mandible are in close proximity to the caudal extent of the caudal maxillary sinus. Radiographically, the caudal limit of the caudal maxillary sinus may be approximated by the ethmoid turbinates caudally, and the frontal sinus caudodorsally.[7]

Ventral Conchal Sinus

The ventral nasal concha is smaller than the dorsal nasal concha. Like the dorsal nasal concha, the ventral nasal concha has a septum dividing it into rostral and caudal parts. The rostral part freely communicates with the nasal cavity, while the caudal part forms the relatively large ventral conchal sinus. Most of the ventral conchal sinus is enclosed within the ventral concha itself, while the remainder of the sinus is within the conchal bulla. The conchal bulla is just ventral to the nasomaxillary opening, resulting in compression of the opening by the conchal bulla. The ventral conchal sinus communicates rostrolaterally with the rostral maxillary sinus over the infraorbital canal.[1] The ventral conchal sinus is ventral to the dorsal conchal sinus, but the dorsal conchal sinus does not extend quite as far rostrally as the ventral conchal sinus. The rostral maxillary sinus extends a little further rostrally than the ventral conchal sinus. The septum that forms the rostral border of the ventral conchal sinus is visible dorsal to the first maxillary molar on a lateral radiograph.[7] The ventral conchal sinus is immediately dorsal to the ventral nasal meatus and a hole may be made through the floor of the ventral conchal sinus to improve drainage from the rostral maxillary sinus and ventral conchal sinus into the nasal cavity.[1, 3, 17]

Middle Conchal Sinus

The dorsal and ventral nasal conchae are much larger than the middle nasal conchae.[1] The caudal part of the middle concha is part of the ethmoidal conchae.[6] The middle conchal sinus is contained in the middle nasal concha. The middle conchal sinus is much smaller than the dorsal and ventral conchal sinuses and is usually of little clinical concern.[3] Laterally, the middle conchal sinus communicates with the caudal maxillary sinus.[1] Boundaries of the middle conchal sinus are not usually visible radiographically.[7]

Sphenopalatine Sinus

The sphenopalatine sinuses are located ventral to the neurocranium and are housed within the sphenoid and palatine bones. The sphenoid bone is made up of the more rostral presphenoid bone and the relatively caudally located basisphenoid bones. These are joined by a cartilaginous joint in immature animals, but this junction becomes ossified as the horse ages, forming the sphenoid bone. The sphenoidal sinus is located within the presphenoid bone. The palatine bone is composed of a horizontal portion that forms the hard palate and a vertical portion that forms part of the lateral wall of the nasopharynx. The palatine sinus is housed within the vertical portion of the palatine bone. In most horses, the sphenoidal and palatine sinuses communicate ventral to the ethmoidal labyrinth, forming the sphenopalatine sinus. A bony septum separates the right and left sphenopalatine sinuses.[2] The septum is usually not located in the median plane in the sphenoidal sinus. The palatine sinus has a large communication with the caudomedial aspect of the caudal maxillary sinus.[1] The communication between the caudal maxillary sinus and the sphenopalatine sinus is obliquely oriented between the caudal end of the infraorbital foramen and the orbit caudal to the last molar.[11] The sphenoidal and palatine sinuses are separated by a bony transverse septum in approximately one-third of horses. In these horses, the sphenoidal sinus communicates with the ethmoidal meatuses.[1] The sphenopalatine sinuses are not usually seen radiographically because of superimposition of the rami of the mandibles. They appear as small radiolucent structures ventral to the cranial vault and caudal to the ethmoid turbinates and extend to the level of the temporomandibular joints in those cases where the sphenopalatine sinuses can be visualized.[7]

McCann, Dixon, and Mayhew transversely sectioned 16 equine heads using a band saw to evaluate variations in anatomy of the sphenopalatine sinus. A great deal of variation in the extent of the sphenoidal sinus and the proximity to vital structures was found. The sphenoidal sinus extended only into the presphenoid bone in seven horses younger than eight years old. The sphenoidal part only occupied the rostral part of the presphenoid bone in two neonates, while one neonate had a sphenoidal part extending to the optic chiasm. Two older horses (16 years and greater than 20 years) had sphenoidal portions extending into the basisphenoid bone. The pituitary glands of these two horses were located very close to the sinus, as was the cerebral arterial circle. Additionally, the maxillary artery and nerve, ophthalmic, oculomotor, abducent, and trochlear nerves, and the ventral petrosal sinus were separated from the sphenoidal sinus by a bony plate less than one mm in thickness. The optic nerves were located close to the sphenoidal sinuses in all cases. As the sphenoidal sinus extended further caudally in the presphenoid bone or into the basisphenoid bone, the optic chiasm, optic tract, and pituitary gland were also closely associated with the sinus. In several cases, small compartments of the sphenoidal sinus surrounded the optic nerve. As a result, disease processes in the sphenoidal sinus may manifest with clinical signs attributable to disorders of any of these structures.

Although the septum between the sphenoidal sinuses was complete in all specimens, there was a great deal of variability in the position of the septum. It was located in a median plane in five of the 16 horses.   In theses horses the left and right sphenoidal sinus drained into the corresponding palatine sinus, which drained into the caudal maxillary sinus. The remaining 11 horses had septae that varied in position, with two horses having septae attached to the lateral wall of the sinus. The palatine sinuses appeared less variable with all 16 horses having left and right palatine sinuses that were fairly symmetrical.

A great deal of variability in drainage routes of the sphenoidal sinuses was observed. The sphenoidal sinuses in the majority of cases drained into the ipsilateral palatine sinus, which drained into the caudal maxillary sinus. Variations of this included drainage from the palatine sinus into the ethmoidal sinus with no communication with the caudal maxillary sinus (this occurred in the one donkey examined, and it is unknown if this occurs in all donkeys or if it occurs in horses), drainage of one sphenoidal sinus into the caudal maxillary sinus via the ipsilateral palatine sinus and drainage of the other sphenoidal sinus directly into the ethmoidal sinus, and drainage of smaller compartments of the sphenoidal sinus into the ethmoidal meatus with drainage of the two main compartments of the sphenoidal sinus into the caudal maxillary sinus via the ipsilateral palatine sinus.[2]

USE OF COMPUTER MODELS IN ANATOMY EDUCATION

The use of interactive 3-D models is a form of active learning, and several studies have shown that active learning is more effective than passive learning. One study utilized a VR environment that allowed users wearing liquid crystal goggles to view virtual objects three dimensionally. Twenty-six volunteers were divided into two groups. One group actively controlled the movement of the 3D object using a box fitted with magnetic sensors that detected the box's orientation. The other group passively watched a recording of another participant's evaluation of the object. All participants were tested by presentation of 20 objects that had been studied using the program and 20 novel, but similar appearing objects. Each object was shown from four different angles.

Participants stated whether they had seen the object during the VR phase of the trial. People who actively studied the objects responded significantly faster than people who studied the objects passively, although there was no difference in accuracy of the response between the two groups. Intermediate views were more accurately identified than views straight from the front, back, and side. Additionally, active participants spent most of their time viewing front, back, and side views plus or minus a few degrees for a longer period of time than they viewed intermediate views. The authors found a similar result when using a trackball rather than a box to control rotation of the objects. A later study found that the active group's advantage disappeared when the response of the object on the screen did not respond as expected to movement of the track ball.[18]

Additionally, studies have indicated that viewing key-views plus or minus a few degrees is as effective, if not more effective, than the learner having control over the images viewed and having a full 360 degree range of views available. In one study 118 psychology students were divided into four groups to study the surface anatomy of the brain: program-controlled key-views, learner-controlled key-views, program-controlled multiple views, and learner-controlled multiple views. Students in the program-controlled views groups performed better than students in learner-controlled groups. Additionally, students with lower innate spatial ability had more difficulty with multiple view presentations. It is unclear if these findings will translate to models of more complex anatomic structures that are more difficult to visualize.[19]

Several studies utilizing a 3-D computer model of the human hand and carpus found students performed better on an exam when they studied multiple views (model rotated by 10 degrees) than students who only looked at key-views 180 degrees apart. One hundred forty-six college anatomy students were divided into two groups, one of which used the key-view model and the other used the multiple view model. The multiple view students had a better understanding of spatial carpal bone anatomy, although the students in this group said they learned a key-view and rotated that view in their heads to answer the questions. The study also found that students' innate spatial ability plays a large role in their ability to learn anatomy.[20] In another study utilizing anatomy of the carpal bones, 87 medical students were divided into two groups with one group viewing a model with 36 different angles of rotation (multiple-view group) and the other group only viewing six views around 0 and 180 degrees (key-view group). Each group viewed the model for three minutes before taking an exam on carpal bone anatomy. The multiple view group performed significantly better than the key-view group. However, there was not a significant difference when differences in spatial ability between each group were taken into consideration, indicating the difference between the two groups was likely the result of innate differences in the test subjects' spatial abilities. Subjects in the multiple view group spent most of their time looking at a few key-views. Utilizing key-views rather than a model that can be rotated through many views may be the most useful way for students to learn the anatomy. This is consistent with hypotheses regarding how people learn 3-D structures in which one or two key-views are learned, and the structure is mentally rotated from that point. It is unknown if more views would be useful with more anatomically complex structures than the carpus.[21] Another study evaluating use of key-views versus multiple views for studying carpal anatomy also indicated that students with low innate spatial ability are disadvantaged by multiple view presentations.[22]

Surgical simulators have been useful in learning anatomy. In one study, 17 medical students were divided into two groups. One group learned the anatomy of the paranasal sinuses using an endoscopic 3-D sinus surgery simulator with haptic feedback, while the other group studied anatomy of the paranasal sinuses from a textbook. Students in the simulator group scored better on a post-training exam and required significantly less time to complete the exam than students in the textbook group.[23]

Another study evaluated the use of a surgical arthroscopy simulator with haptic feedback to learn the anatomy of the shoulder joint. Twenty-nine medical students were divided into two groups with one group spending 10 minutes using the surgical simulator and the other group spending 10 minutes studying a textbook. The students' ability to correctly identify anatomical structures on a surgery arthroscopy video was then tested. There was no significant difference in the test scores of the students in the two groups, indicating the simulator was at least as effective as the textbook. The students using the simulator rated it more highly as a learning tool than students using textbooks and said they were more likely to use it if it were available than students using textbooks.[24]

In another study utilizing a fully rotatable 3-D model of the liver, six general surgery residents took a pre-test, and then underwent a 45 minute workshop with an instructor demonstrating the liver model followed by another exam. The exam was repeated six months later to evaluate retention of the information learned. Residents scored significantly better on the post-test than the pre-test. The six months post-test showed that all residents retained the information learned and several improved their scores from the immediate post-test.[25]

Another group of investigators developed a 3-D model of the middle and inner ear using MRI data. The model was incorporated into an online tutorial that displays text and 2-D images of the middle and inner ear with links to the 3-D model. The user is able to manipulate the model after clicking on a link to it. Fifty-seven students divided into a control group and an intervention group completed the study. Both groups completed an online tutorial using text and 2-D images to be able to recognize and name the structures of the middle and inner ear. Following the tutorial, the students took a quiz to ensure they had learned the names of the structures. The control group then viewed the 3-D relationship tutorial without links to the 3-D model. Students in the intervention group viewed the same tutorial but were able to access the linked 3-D model. Students in both groups then took a quiz evaluating their knowledge of 3-D relationships of the structures of the middle and inner ear. The group viewing the 3-D model scored significantly better than the control group on the post-tutorial quiz. Additionally, students in the intervention group spent significantly more time studying the tutorial than students in the control group. These results are better than the results seen with the carpal model mentioned above and may indicate that interactive 3-D computer models may provide more educational benefit for more complex anatomic structures.[26]

In another study, a 3-D computer model of the pelvic floor was evaluated. Thirteen general surgery residents were given a pre-test on the anatomy of the pelvis and anorectal area. They were then given a lecture by a colorectal surgeon using the unisex pelvic floor computer model to depict the 3-D relationships of the pelvis, anus, and rectum. The residents were then given an exam over the material. Post-test scores were significantly better than pre-test scores.[27]

STATEMENT OF PURPOSE

The equine paranasal sinuses are a common site of disease. Primary or secondary sinusitis, ethmoidal hematomas, sinus cysts, foreign bodies, trauma and neoplasia of the paranasal sinuses can all cause significant illness in horses. Correct identification of the affected sinus(es) is essential for diagnosis and treatment of these diseases. Because the anatomy of the equine paranasal sinuses is complex and the sinuses are encased in bone, it is difficult to visualize individual sinuses when studying anatomy, performing physical examinations, and evaluating radiographs of the equine head. 3-D computer models have shown promise as aids for learning anatomy, especially anatomy of complex structures that are difficult to visualize. The purpose of this thesis was to generate an interactive 3-D computer model of the equine paranasal sinuses that can be rotated to demonstrate the relationships between the different sinuses and the bones of the skull. The successful computer program should be easy to use, improve the user's understanding of the anatomy of the equine paranasal sinuses, and enable the user to more accurately identify the paranasal sinuses radiographically and surgically.

CHAPTER II

MATERIALS AND METHODS

ANIMAL AND IMAGE ACQUISITION

The head of a 15 year old sorrel Quarter Horse mare was obtained from the pathology service of the Texas A&M University Veterinary Medical Teaching Hospital three days post-euthanasia. The horse was euthanized as a result of severe fibrinonecrotic colitis, and she had no history of respiratory disease. The head was stored for approximately 48 hours in plastic bags in a cooler in the gross anatomy lab. The head was taken to Texas A&M Institute for Preclinical Studies where the outside of the bag was sprayed with disinfectant and the head and bag were placed on the bed of a 128 slice Siemens Biograph mCT PET/CT scanner. A CT scan of the horse's head was performed using a high spatial resolution ("bone") algorithm and two mm thick slices.

GENERATION OF TWO-DIMENSIONAL IMAGES OF SKULL AND SINUSES

The images generated by the CT scan were copied to a DVD and sent to Nighthawk Radiology Services for 3-D reconstruction using Terra Recon software. A 3-D model was generated and the opacity of the bones of the skull was reduced to make the skull more transparent, enabling visualization of osseous structures within the skull. Although the reconstruction was three-dimensional, saving images of the reconstructions can only be done in two-dimensional (2-D) file formats. By scrolling through bitmap images from a sample horse head 3-D reconstruction in Microsoft Power Point, it was determined that saving images of the 3-D reconstructions every three degrees would result in a model that would rotate smoothly when the computer program was generated. Key-views plus or minus nine degrees were saved as JPEG files. The key-views chosen were right and left lateral views, 45 degree right and left dorsal oblique views, and a dorsoventral view.

The dorsoventral view was imported into Adobe Photoshop 6.0 and became the background layer. The margins of each sinus was traced in a different layer, and each pair of sinuses was represented by a different color: the rostral maxillary sinuses were purple, the caudal maxillary sinuses were blue, the frontal sinuses were lime green, the dorsal conchal sinuses were orange, the ventral conchal sinuses were hunter green, and the sphenopalatine sinuses were red. For each pair of sinuses, the CT scan of the horse head, descriptions of the extent of the sinuses, textbook illustrations, and skulls from a veterinary anatomical laboratory were used to identify the boundaries of the sinuses on the reconstructed images. Using the pen tool with the rubber band option selected, each sinus was outlined and the path was filled using the color corresponding to that sinus. The opacity of the layer was decreased to 50 percent so it was possible to see the bones of the skull through the shaded sinuses. The image was saved with the individual layers intact.

Once all the sinuses were filled in on the dorsoventral view, all layers were merged and the image was saved as a new file. The image showing the reconstruction three degrees left of dorsoventral was opened and the reconstruction became the background layer. A second layer was created and the image showing the merged layers of the dorsoventral view was pasted into this layer. The dorsoventral image was aligned rostrally and caudally with the background layer. The layer containing the right rostral maxillary sinus was copied from the dorsoventral image and pasted into a new layer in the three degrees left of dorsoventral image. The pasted right rostral maxillary sinus was lined up with the right rostral maxillary sinus on the merged dorsoventral image. The pen tool was used as described for the dorsoventral view to draw the right rostral maxillary sinus in an empty layer and fill the path with the color corresponding to the rostral maxillary sinuses. The opacity of the layer was reduced to 50 percent. This process was repeated for the remaining sinuses. The process used to create the image illustrating the sinuses three degrees left of dorsoventral was repeated for the remaining oblique views around dorsoventral: six degrees left of dorsoventral, nine degrees left of dorsoventral, three degrees right of dorsoventral, six degrees right of dorsoventral, and nine degrees right of dorsoventral.

The JPEG image depicting the left lateral reconstruction was opened in Adobe Photoshop 6.0. The JPEG image became the background layer. Because the right and left sinuses are superimposed on a lateral view, the outline of each sinus corresponded to right and left sinuses of the same name. The dorsoventral image with sinuses merged into a single layer was rotated 90 degrees counter-clockwise and pasted into a new layer on the left lateral image. The rostral and caudal margins of the skull on the dorsoventral view were aligned with the rostral and caudal margins on the left lateral view. Using the sinuses on the dorsoventral view as guides to the rostral and caudal margins of each pair of sinuses as well as descriptions of the extent of each sinus, illustrations from textbooks, and a skull from a veterinary anatomical laboratory, each pair of sinuses was drawn in an empty layer with the pen tool as described above and the path filled using the color corresponding to each sinus. The opacity of each layer was decreased to 50 percent. The image was saved with all layers intact. The background layer and the layers depicting each pair of sinuses were merged and saved as a separate image.

The three degrees dorsal to left lateral image was opened in Adobe Photoshop 6.0 and made the background layer. The left lateral view with the illustrated sinuses and background layer merged was pasted into a new layer in the three degrees dorsal to left lateral image. The rostral and caudal margins of the skull were aligned with the background layer. The rostral maxillary sinus was copied from the left lateral image and pasted into a new layer in the three degrees dorsal to left lateral image. The rostral maxillary sinus was aligned with the rostral maxillary sinus on the merged left lateral layer. Using the rostral maxillary sinus from the left lateral view as a guide, the right rostral maxillary sinus was drawn using the pen tool. The path was filled with the color corresponding to the rostral maxillary sinuses, and the opacity of the right rostral maxillary sinus layer was decreased to 50 percent. This process was repeated for the remaining sinuses on the three degrees dorsal to left lateral view. This process was repeated for the remaining oblique views around left lateral: six degrees dorsal to left lateral, nine degrees dorsal to left lateral, three degrees ventral to left lateral, six degrees ventral to left lateral, and nine degrees ventral to left lateral.

The right lateral view was opened in Adobe Photoshop 6.0 and made the background layer. Because the right lateral view and its oblique views are 180 degrees from the left lateral view and its corresponding oblique views, the left lateral view and its associated obliques could be rotated and pasted into the corresponding right lateral and oblique views. The left lateral image with all of the sinuses and background merged into one layer was opened. The image was flipped horizontally. The image was copied and pasted into a new layer in the right lateral image. The margins of the skull from the left lateral view were aligned with the margins of the skull in the right lateral view. The left lateral view with the background layers and each pair of sinuses in separate layers was opened. The image was flipped horizontally. The layer depicting the rostral maxillary sinuses was copied and pasted into a new layer on the right lateral view. The opacity of the layer was decreased to 50 percent. This process was repeated for the remaining layers. The resulting image was saved.

The three degrees dorsal to right lateral image was opened in Adobe Photoshop 6.0 and made the background layer. The three degrees ventral to left lateral image was used as a guide. The process used to create the right lateral view was repeated for each sinus in the three degrees dorsal to right lateral image. This process was repeated for the following views: six degrees dorsal to right lateral, nine degrees dorsal to right lateral, three degrees ventral to right lateral, six degrees ventral to right lateral, and nine degrees ventral to right lateral.

The 36 degrees dorsal to left lateral image was opened in Adobe Photoshop 6.0 and made the background layer. The nine degrees dorsal to left lateral view with all of the layers illustrating the sinuses and background layer merged into one layer was copied and pasted into a new layer in the 36 degrees dorsal to left lateral image. The rostral and caudal margins of the skull were aligned with the rostral and caudal margins of the skull on the background layer. The nine degrees dorsal to left lateral image was opened. The right rostral maxillary sinus layer was copied and pasted into a new layer in the 36 degrees dorsal to left lateral image. The pasted sinus was aligned with the corresponding sinus in the layer depicting the nine degrees dorsal to left lateral merged sinuses. Using the rostral and caudal margins as a guide along with a skull from a veterinary anatomical laboratory, the margin of the right rostral maxillary sinus was drawn using the pen tool, and the path was filled with the color corresponding to the rostral maxillary sinuses. The opacity of the layer was reduced to 50 percent. This was repeated for the remaining sinuses. The resulting image was saved. The layers illustrating each sinus and the background layer were merged into one layer and saved as a separate image. This process was repeated for the following views: 39 degrees dorsal to left lateral, 42 degrees dorsal to left lateral, 45 degrees dorsal to left lateral, 48 degrees dorsal to left lateral, 51 degrees dorsal to left lateral, and 54 degrees dorsal to left lateral. The same process was utilized to illustrate the 36 degrees dorsal to right lateral, 39 degrees dorsal to right lateral, 42 degrees dorsal to right lateral, 45 degrees dorsal to right lateral, 48 degrees dorsal to right lateral, 51 degrees dorsal to right lateral, and 54 degrees dorsal to right lateral views. Finally, the eraser tool was used to remove text and other markings from all images.

GENERATION OF INTERACTIVE COMPUTER PROGRAM

Adobe Flash Professional CS 5 was used to create an interactive computer program. The stage size was changed to 900 pixels wide by 400 pixels high and the color was changed to black to create a continuous background with the images. The scene that appeared when Flash first opened was renamed "Intro." The first keyframe became the title screen. The image depicting all of the sinuses on the left lateral view was opened in Adobe Photoshop. The image height was reduced to 400 pixels, the height of the stage. The aspect ratio was locked, so the image width decreased correspondingly, and the image was saved as a Photoshop file and as a JPEG. In Adobe Flash, the JPEG copy of the left lateral image illustrating all sinuses was imported to the stage in the first keyframe. Title text was added in a separate layer. A "Click here to begin" button was created and added to a separate layer. The button contained a hidden rectangular hit area over the "Click here to begin" text, so the button was activated anytime the user clicked within the rectangle. The button was selected and given an instance name. The Actions panel was opened, and the Timeline Navigation folder was expanded from the Code Snippets panel. "Click to Go to Next Frame and Stop" was selected. The Actions Panel was again opened and "Stop at This Frame" was selected from the Code Snippets panel, preventing the movie from progressing to the next frame without the user clicking the "Click here to begin button."

The next frame became the menu screen for the program. The frame was converted to a blank keyframe. Text was added to provide a menu heading and instructions for the user to click a button to view the sinuses specified by each button. A layer was created for buttons. A “Stop at This Frame” command was added to prevent the timeline from advancing without input from the user.

A new scene was created and named “Rostral Maxillary Sinuses.” The image depicting the sinuses nine degrees ventral to left lateral was opened in Adobe Photoshop. The image was flipped horizontally and the height was resized to the stage size with a corresponding decrease in the width of the image. Only the background, right maxillary sinus, and left maxillary sinus layers were made visible. The image was resaved as a Photoshop document and a copy was saved as a JPEG. In Adobe Flash, the JPEG image was imported to the stage. The next frame was converted to a blank keyframe. The six degrees ventral to left lateral image was modified using Adobe Photoshop similar to the modifications made to the nine degrees ventral to left lateral image. The resulting image was imported to the second frame of the “Rostral Maxillary Sinuses” layer in Adobe Flash. This process was repeated for the remaining left lateral images and associated key-views, as well as the 45 degrees dorsal to left lateral plus or minus nine degrees, with each image being placed in the subsequent blank keyframe. In Adobe Photoshop, the image depicting the sinuses nine degrees left of dorsoventral was opened. The width of the image was reduced to the size of the Adobe Flash stage, 400 pixels with a corresponding decrease in the height of the image. The image was rotated clockwise 90 degrees. The background, right rostral maxillary sinus, and left rostral maxillary sinuses layers were the only layers visible. The image was saved as a Photoshop document and as a JPEG. The JPEG was imported into a blank keyframe following the 54 degrees dorsal to left lateral view. This process was repeated for the remaining dorsoventral and its oblique views. This process was repeated for the 45 degrees dorsal to right lateral and associated views and the right lateral and associated oblique images, only the images were flipped vertically rather than being rotated 90 degrees clockwise and the heights were changed to stage size rather than the widths. In order to prevent the movie from continuing past the first frame without input from the user, ActionScript telling the movie to stop at that frame was added to the first keyframe.

Once all of the images were imported into Adobe Flash, buttons were created to navigate the images. A new layer was created and titled "Buttons." A button was created using a U-turn arrow imported from Microsoft Word. The hit area of the button was a hidden rectangle around the arrow. The button was placed on the "Buttons" layer in the first keyframe at 490 on the X axis and 340 on the Y axis, selected using the selection tool, and given an instance name. The Actions panel was opened and "Click to Go to Next Frame and Stop" was selected from the Timeline Navigation folder of the Code Snippets panel. The last frame in this scene was converted to a keyframe. The U-turn arrow button in this frame was given a different instance name with no action linked to it.

A similar button was created to scroll through the images in the opposite direction. The same U-turn arrow from Microsoft Word was used, but was flipped horizontally. It also had a hit area corresponding to a hidden rectangle around the arrow. The second frame in the buttons layer was converted to a keyframe, and the newly created button was placed at 490 on the X axis and 280 on the Y axis, selected with the selection tool, and given an instance name. In the Actions Panel, "Click to Go to

Previous Frame and Stop" was selected from the Timeline Navigation folder of the Code Snippets panel. The same button was added to the first keyframe, but a difference instance name was assigned to it. No action was associated with this instance of the button.

A third button was created, enabling the user to return to the menu. "Exit to Menu" was added as button text, with a hidden rectangle hit box outlining the text area. The button was added to the first keyframe of the buttons layer at 35 on the X axis and 340 on the Y axis. The button was selected and given an instance name. "Go to Scene and Play" was selected from the Timeline Navigation folder of the Code Snippets panel. In the ActionScript, "Scene 3" was replaced with "Intro" and the number one prior to the Scene name was changed to 2, indicating when the button was clicked, the program should return to Frame two of the Intro scene, the menu screen.

On frame two of the "Intro" scene, a button was created to navigate users to the Rostral Maxillary Sinuses scene just created. The button consisted of "Rostral Maxillary Sinus" as text with a hidden rectangle outlining the text box as a hit area. From the Timeline Navigation folder of the Code Snippets panel in the Actions panel, "Go to Scene and Play" was selected. In the ActionScript box, "Scene 3" was changed to "Rostral Maxillary Sinuses." The movie was tested in Adobe Flash Professional and saved. The process to create the "Rostral Maxillary Sinuses" scene was repeated for the following scenes: Caudal Maxillary Sinuses, Frontal Sinuses, Dorsal Conchal Sinuses, Ventral Conchal Sinuses, Sphenopalatine Sinuses, and All Sinuses. For each scene, the sinuses corresponding to the name of the scene were highlighted on each Photoshop image and the resulting images were saved as JPEG images prior to importing into Adobe Flash.

Each scene illustrating paranasal sinuses was converted to two movie clips. For the first movie clip, all layers and frames from the corresponding scene were copied. A movie clip symbol was inserted. The copied layers and frames were pasted into the timeline of the movie clip. The arrow navigation buttons were moved closer to the image of the skull. Another movie clip symbol was inserted. The copied layers and frames from the original scene were pasted into the timeline of the movie clip. The "Exit to Menu" button and its ActionScript were deleted from this movie clip. The image of the skull and sinuses was rotated 90 degrees counter-clockwise. The navigation buttons for this movie clip were moved closer to the skull image. The layers and frames were deleted from the original scene, and the two newly created movie clips were placed on the stage in the first frame of the scene corresponding to the sinuses illustrated in the movie clips.

Prior to publication, final adjustments were made to each movie clip. Any remaining marks and lines on the images were covered using black rectangles that blended in with the image background and stage. For each movie clip depicting a single pair of sinuses with rostral facing left, a text box was added at the top of the stage indicating the sinuses shown. For the movie clip illustrating all pairs of sinuses with rostral facing left, a color key was added to the top of the stage showing which color illustrated each pair of sinuses. Finally, the movie was published in a Windows projector.

CHAPTER III

RESULTS AND DISCUSSION

The horse had no evidence of disease of the paranasal sinuses on the CT scan. A small amount of fluid was present in the caudal maxillary sinuses (Figure 1), but this was considered a post-mortem change. CT is an optimal imaging modality for visualizing the relationship between the paranasal sinuses and the skull because of the contrast between the air in the paranasal sinuses and the bony skull. Reconstruction of the CT scan images yielded high-quality images. Many features of the skull remain visible even with the opacity of the skull reduced (Figure 2). Based on evidence in the literature that suggests viewing key-views plus or minus a few degrees is as effective as viewing a model that can be rotated through a full 360 degrees of rotation, only key-views plus or minus nine degrees were included. The key-views included in this thesis were selected because they correspond to commonly utilized radiographic views in the evaluation of the paranasal sinuses.

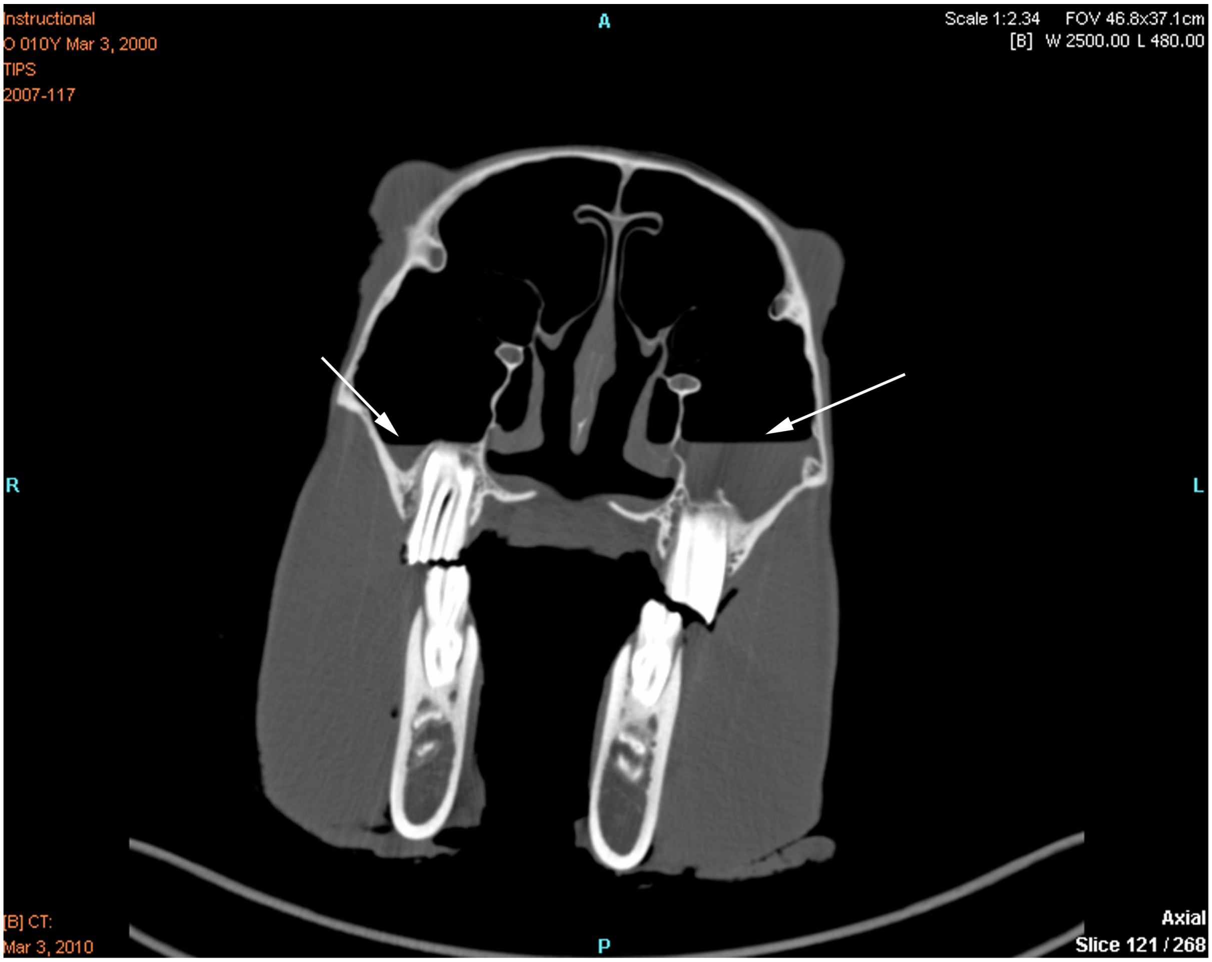

Figure 1: Transverse CT image at the level of the third maxillary molar. The arrows indicate fluid in the right and left caudal maxillary sinuses. The fluid was considered to be a post-mortem change rather than the result of a pathologic process.

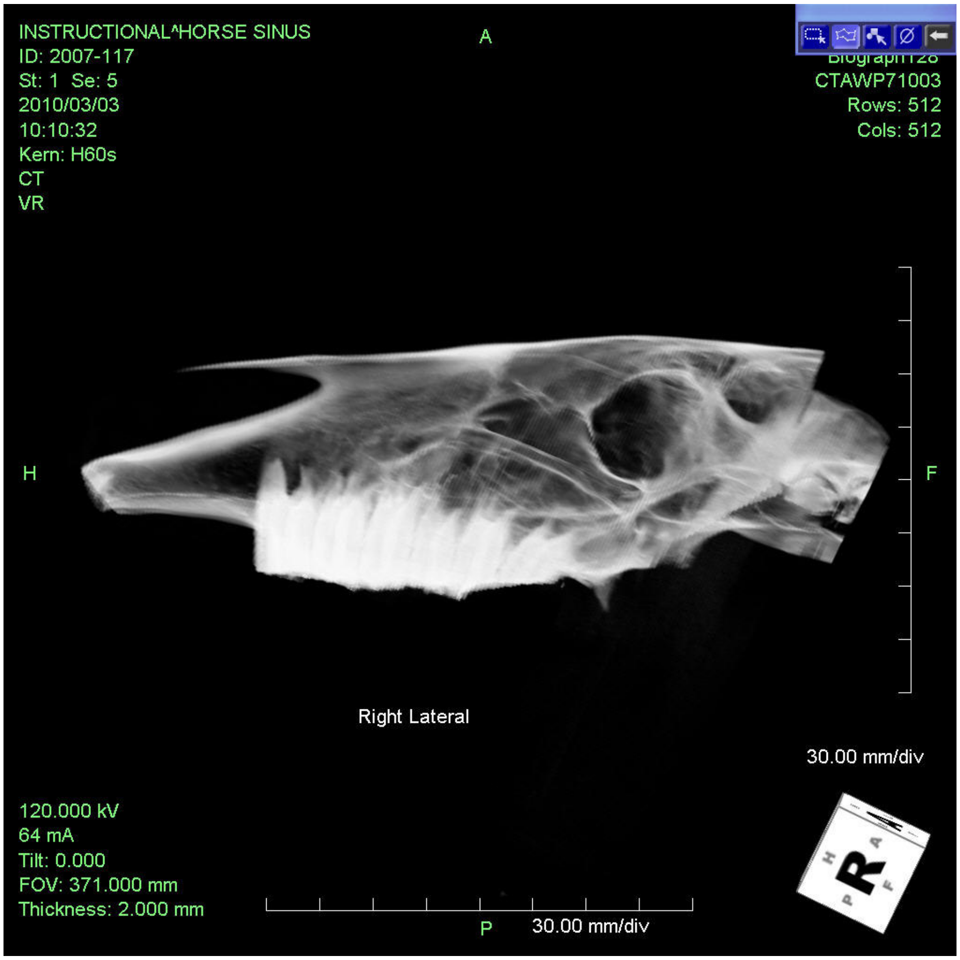

Figure 2: 3-D reconstruction of horse's skull.

Using Adobe Photoshop to manipulate the images and illustrate the sinuses was time-consuming, but provided the necessary tools to create the final images. The pen tool allowed detailed outlining of complex structures. Figure 3 depicts use of the pen tool to outline the right caudal maxillary sinus on the dorsoventral view. With the exception of the dorsoventral view, which was illustrated first, previously completed images aided in the illustration of subsequent images. For changes in rotation greater than three degrees, a completed image was used to aid identification of rostral and caudal margins of the sinuses. Figure 4 shows how the dorsoventral view was used to aid identification of the rostral and caudal margins of the sinuses on the right lateral view. Because there is not a substantial difference in sinus size and shape through three degrees of rotation, completed images could be used as guides to aid in identification of sinus boundaries for images whose orientation differed by three degrees (Figure 5). After outlining and filling each sinus, the opacity of the layer was reduced to 50 percent, which enabled adequate visualization of the underlying structures of the skull. Figure 6 is an example of a completed image. Because of the lack of clinical significance of the middle conchal sinus, it was excluded from the illustrations.

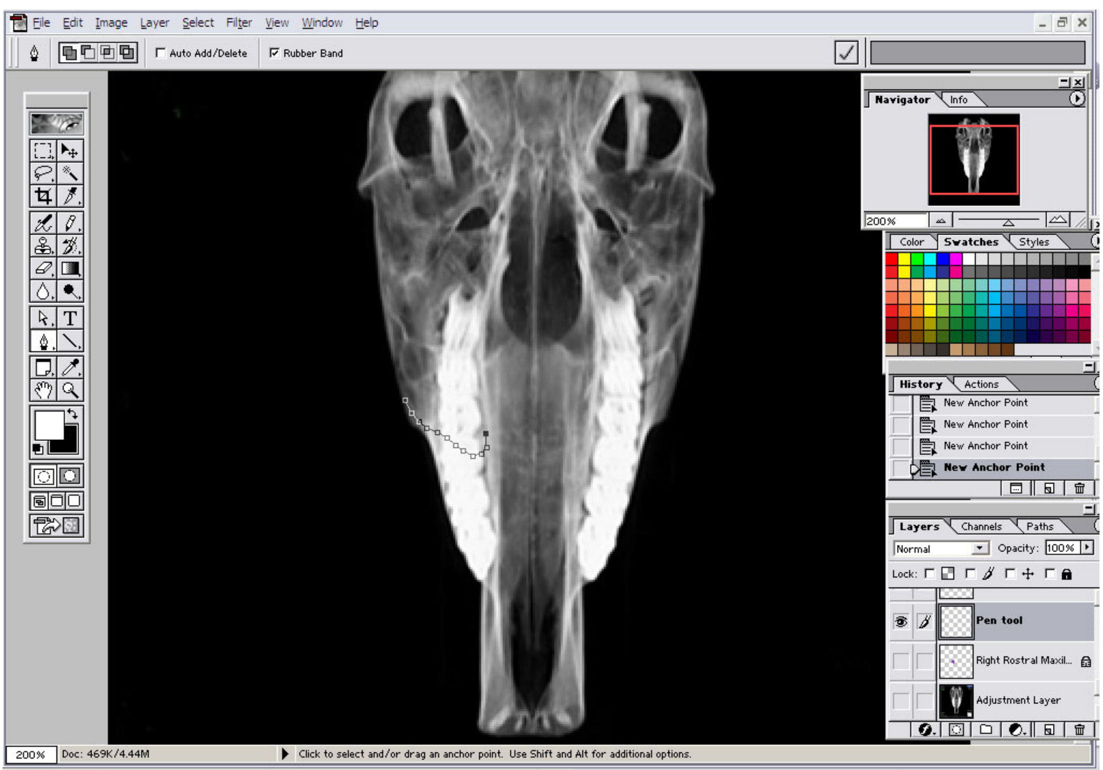

Figure 3: Use of the pen tool to outline the right caudal maxillary sinus. Upon completion of outlining the sinus, the path was filled with the color corresponding to the maxillary sinuses and the opacity of the layer was reduced to 50 percent.

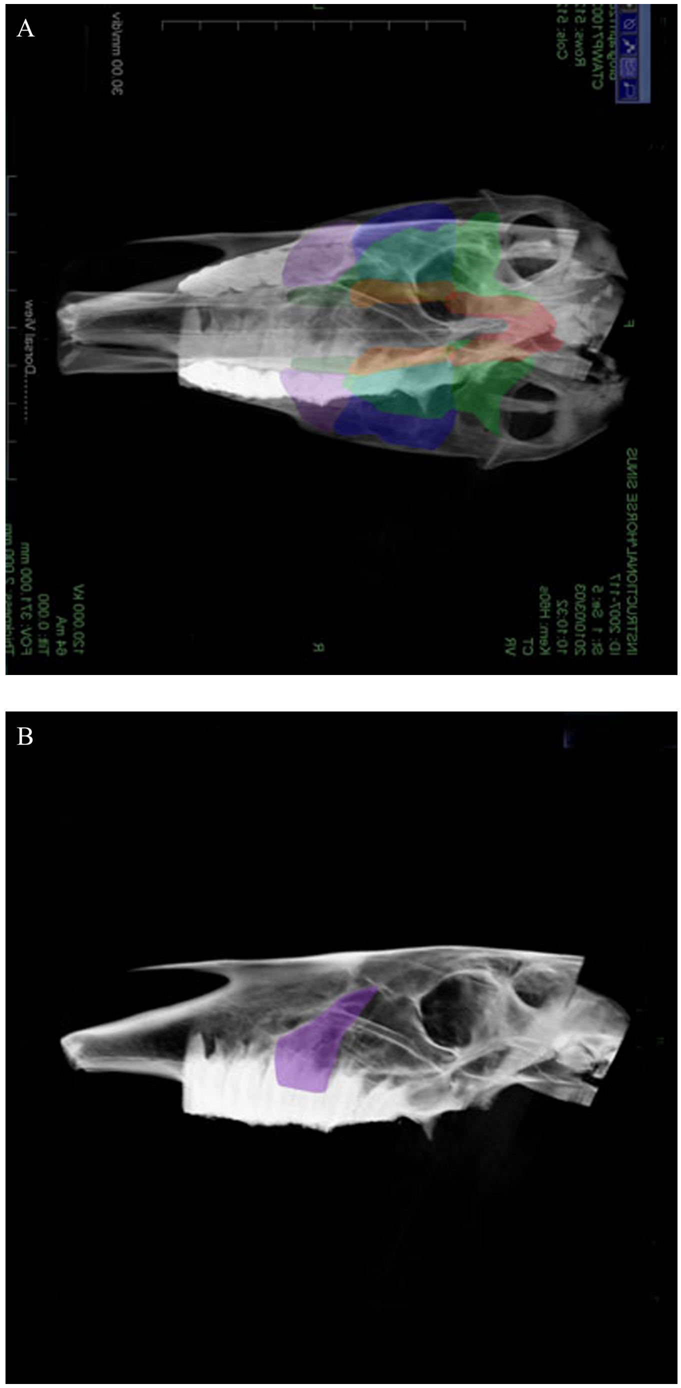

Figure 4: Use of dorsoventral view to illustrate right lateral view. The layers of the completed dorsoventral view were merged. The resulting image was rotated and pasted into a new layer in the left lateral view. The rostral and caudal margins of the skull on the dorsoventral view were aligned with the corresponding margins on the lateral view (A). The rostral and caudal margins on the dorsoventral view were used to help identify the rostral and caudal margins of the rostral maxillary sinus on the lateral view (B).

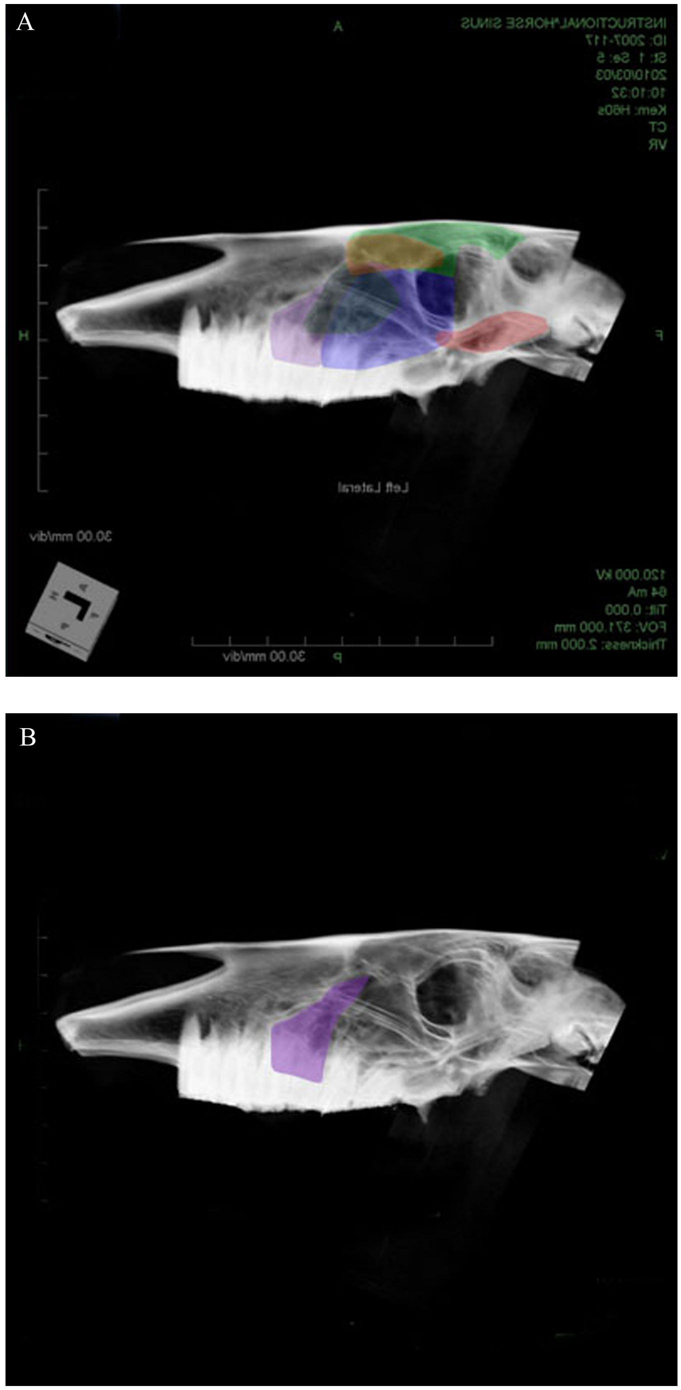

Figure 5: Use of completed left lateral image to illustrate image three degrees dorsal to left lateral. All layers from the left lateral image except the layer showing the sinuses on the dorsoventral view were merged and pasted into a new layer in the three degrees dorsal to left lateral image. The rostral and caudal margins of the skull were aligned on both views (A). The sinuses on the left lateral image were used as a guide to the margins of the sinuses on the three degrees dorsal to left lateral image (B).

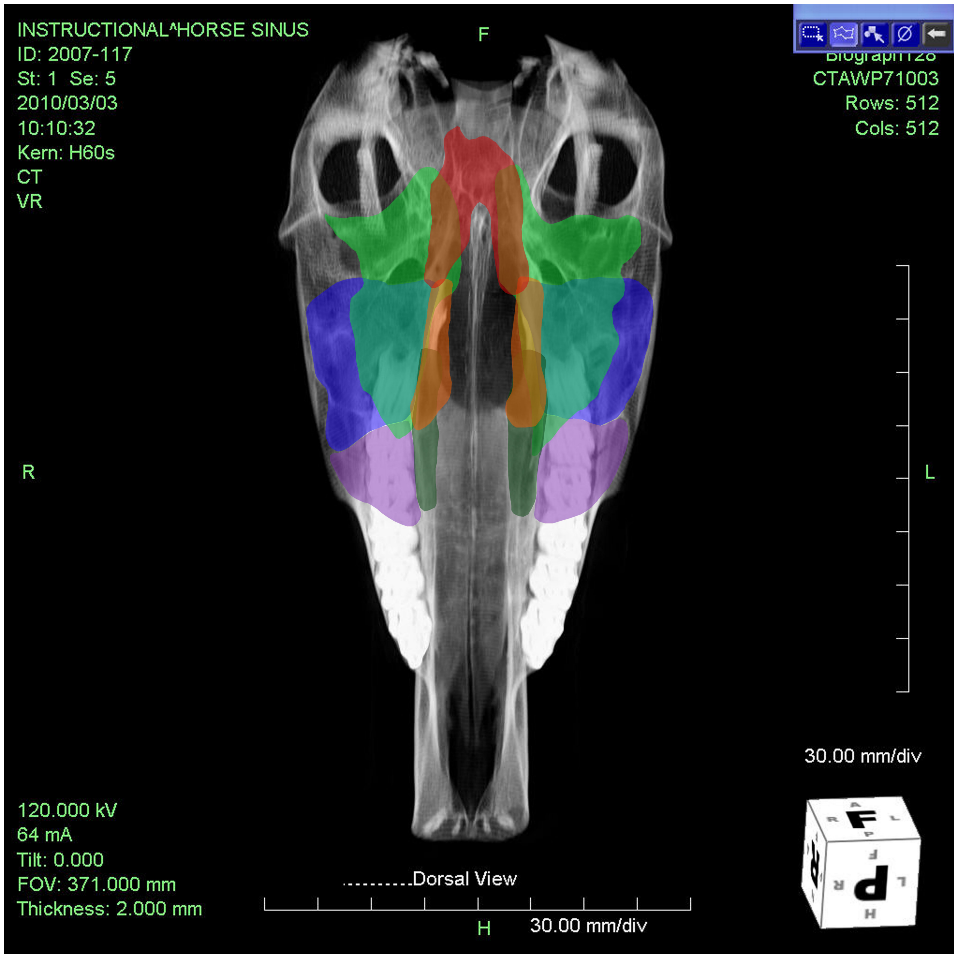

Figure 6: Completed dorsoventral view.

Adobe Flash Professional CS5 provided an effective means of creating the interactive computer program. The resulting computer program is easy to use and provides illustrations of the sinuses from a variety of angles that is not readily found in the literature. Because the dorsoventral view is most commonly viewed radiographically with rostral oriented downward, while lateral and 45 degree oblique views are viewed with rostral oriented toward the left, both orientations were provided using two movie clips displayed together on the stage. This allowed independent navigation of the two orientations (Figure 7).

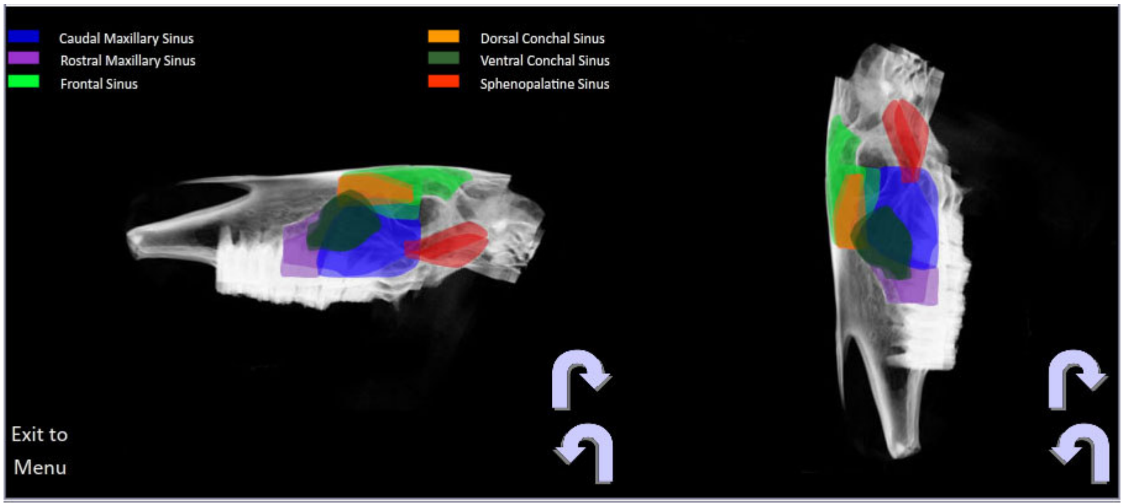

Figure 7: Two movie clips with independent navigation buttons displayed simultaneously in completed program.

Rather than creating a traditional movie for a website, the movie was published in a stand-alone Windows viewer, allowing easy dissemination to users. The Code Snippets panel available with ActionScript 3.0 makes simple programming tasks user friendly. For programs such as the one created in this thesis, the programmer may not have vast amounts of computer programming experience. Because the basic animation tools are relatively easy to use, similar programs could be developed fairly easily without requiring the services of a computer programmer.

Simple buttons were easily created to allow navigation through the program. ActionScript from the Timeline Navigation folder of the Code Snippets panel provided the basic commands for the buttons to allow the user to navigate through the program

(Figure 8). The arrow buttons in the movie clips illustrating each pair of sinuses and all sinuses together were placed in a keyframe in the first frame of each movie clip. They appear in the remaining frames of that scene. A second instance of each button was added to each movie clip. For the button with the command to “Go to Previous Frame and Stop,” the second instance of the button was added to a keyframe in the second frame. This instance of the button had the command “Go to Previous Frame and Stop” linked to it. The first instance of this button in the first frame had no command associated with it and was therefore inactive. This prevented the program from moving to another scene if the button was clicked on the first frame. Likewise, for the button instructing the program to “Go to Next Frame and Stop” the instance in the first frame had the ActionScript command linked to it. However, a second instance of the button was added to the last frame and had no command associated with it. This prevented the program from moving to another scene if the user clicked the button while viewing the last scene.

The movie clips depicting all of the sinuses illustrates the relationships between the individual sinuses well. Features of the skull are visible through the sinuses. However, because of the number and overlap of the sinuses, it is somewhat difficult to easily identify the relationships of the sinuses and the skull. As a result, scenes illustrating the individual sinuses were included to more easily establish the relationship between the sinuses and the skull.

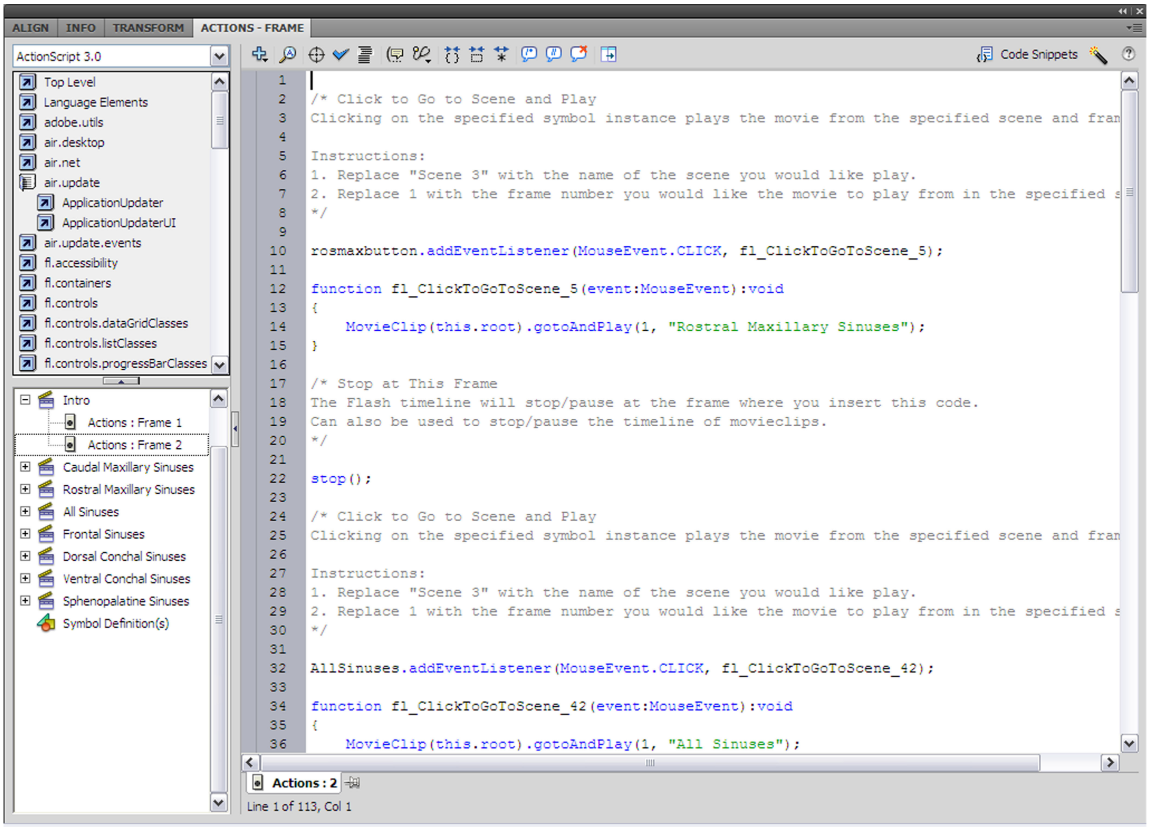

Figure 8: ActionScript defining actions for buttons on Menu screen.

CHAPTER IV

CONCLUSIONS

The equine paranasal sinuses are a frequent site of disease. Because the paranasal sinuses are encased in bone, it is difficult to learn their anatomy and visualize them accurately. As a result, accurate interpretation of radiographic changes associated with the paranasal sinuses can be difficult. Additionally, therapeutic and diagnostic approaches to the sinuses may be difficult to visualize and understand for the inexperienced practitioner. 3-D computer models are being used increasingly in anatomy education with varying results. Based on the literature currently available, a 3-D computer model providing key-views plus or minus a few degrees may aid in the understanding of the anatomy of complex and difficult to visualize structures. The computer program developed through this thesis is easy to use and provides illustrations of the sinuses from a variety of angles that are not readily found in books. Prominent features of the skull are readily visible in the illustrations, aiding understanding of the anatomy of the sinuses.

The techniques used in the development of this thesis could be used to develop this program further. Scenes illustrating combinations of the various sinuses could be added. The menu screen could be changed to allow the user to check the boxes of the sinuses they want to view. The biggest limitation to this would be the number of scenes created and the file size of the resulting program. This would take the program longer to load which may frustrate users.

Using CT scan data to generate 3-D reconstructions is effective for structures that are visualized well with CT. The currently available 3-D reconstruction software allows many ways to manipulate images to create the effect the user is looking for. If needed, additional image manipulation may be done using Adobe Photoshop. Adobe Flash provides a useful and relatively simple means of computer program development. Computer programs illustrating other anatomically complex structures could be easily developed using the techniques described in this thesis to aid the currently available resources for anatomical education. Because Adobe Flash is reasonably easy to use, users without a significant amount of experience in computer program could use it to develop programs themselves, eliminating the expense of employing a capable programmer.

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APPENDIX

The computer program demonstrating the equine paranasal sinuses created in this thesis is included as a separate file.

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