**University of Alberta**

# The Attraction to New Techniques: Using Magnetic Resonance Imaging to Evaluate the Morphology of the Frontal Sinuses of Monozygotic Twins

by

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requirements for the degree of Master of Arts

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## Abstract

This research sought to investigate the use of Magnetic Resonance Imaging (MRI) to physical anthropology, and to look at the shape similarities in the frontal sinuses of monozygotic twins using MRI.

MRI is an imaging technology employed in the medical field. The frontal sinuses exist between the inner and outer tables of bone in the forehead, and are often used to establish personal identification in forensic contexts.

Nine pairs of monozygotic twins were compared using maximum height, width, depth, volume and qualitative descriptors. Intra- and interobserver errors were examined and basic statistical analyses performed. The results show that only some twins were similar to each other. Considerable variation between twin pairs was seen. MRI was concluded to be useful to soft and hard tissue studies.

With the increasing employment of new technologies by the medical field, physical anthropologists must become familiar with these scans to continue to establish personal identity.

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# Chapter One - Introduction

The frontal sinuses have long been used by forensic anthropologists and pathologists to distinguish and resolve personal identity in forensics cases. Images of the frontal sinuses are most often acquired through the use of traditional plane film X-ray and occasionally computerized tomography (CT) scanning. A search of the literature reveals that rarely, if ever, are the frontal sinuses examined using magnetic resonance imaging (MRI). The major advantage from a forensic perspective is that the morphology of the frontal sinuses can be used for determining identity when other techniques are not applicable. For instance, if a body is edentulous then dental records are of no use in identification; likewise if the remains are burnt, mutilated or submerged in water, then fingerprints and visual identification are of limited use (Marlin et al., 1991). The frontal sinuses are located between the inner and outer tables of bone in the forehead region (Scheuer & Black, 2000), an area frequently undamaged in forensic contexts.

Frontal sinus patterns have most often been viewed on traditional plane film radiographs. The ease, widespread availability and low cost of X-ray equipment mean that this is a popular mode of image capture. For examination of the frontal sinus there are some distinct disadvantages in using X-ray images in this format. Firstly, these radiographs only depict three dimensional objects in two dimensions. Secondly, this method of image acquisition superimposes structures making it difficult to visualize small regions (Christensen, 2005). Thirdly, the technology employed in traditional radiograph imaging results in the patient being subjected to small doses of potentially harmful radiation.

More recent techniques such as computerized tomography (CT) and magnetic resonance imaging (MRI) are becoming more widespread in their application (Smith et al., 2002). These technologies both produce three dimensional information or images and do not superimpose small anatomical structures. CT is better at imaging bone structures (Shankar et al., 1994:30), but like X-rays it works by irradiating the subject. MRI is being increasingly used in the medical field especially to acquire images of soft tissues. MR technology is often preferred to diagnose tumors, strokes, degenerative diseases, inflammation, infection and other abnormalities in organs and other soft tissues of the body (Imaging Advisory Committee, 2001). Moreover, the use of radio waves and strong magnetic fields to create magnetic resonance images means that this imaging modality is safer for patients and volunteers since there is no damaging radiation exposure involved. The increased use of CT and MR imaging for the head and neck means that the antemortem record being generated by hospitals and clinics is shifting away from traditional radiographs. In the future, forensic anthropologists and pathologists will have to deal with antemortem records which contain images of the frontal sinuses generated from CT and MR scans.

Several anthropological studies (Reichs and Dorion, 1992; Reichs, 1993; Haglund and Fligner, 1993; and Smith et al., 2002) have compared the frontal sinuses on ante- and postmortem CT images. This research has produced promising results in the visualization and comparison capabilities of computerized tomography images of the frontal sinuses. To date, no similar research has been published using MR images to look at the frontal sinuses.

The frontal sinuses have been previously examined on related individuals, including identical twins. Twin studies are important, especially when looking at a structure such as the frontal sinuses that are used to establish personal identity. Research using monozygotic twins, who are genetically identical, provides essential information on the degree to which environmental factors, such as nutrition, disease and trauma, alter structure and shape of the frontal sinuses. This research also looks at the personal uniqueness of the frontal sinuses, something that is called upon in forensic contexts. Twin studies focusing on the frontal sinus (Turpin et al., 1942; Schuller, 1943; Asherson, 1965; Dillon and Gourevitch, 1936; Maresh, 1940) illustrate that there are differences between monozygotic twins, but especially between fraternal twins, which increase with age until adulthood when growth is completed (Turpin et al., 1942). Asherson (1965) found that, in every one of 74 pairs of twins, there was a difference in the pattern of the frontal sinus. He also noted that, in over 2000 cases examined, he had never found two identical frontal sinus patterns (cited in Quatrehomme et al., 1996). The current study marks the first time that data from identical twins has been compared using images acquired from MRI.

The project reported in this thesis had two research goals. The first was to examine and evaluated the use of MRI to physical anthropology research problems. MRI has been used in the past to look at prehistoric mummies (Notman et al., 1986) as well as to aid in contemporary autopsies (or virtopsies) (Thali et al., 2003). MRI provides information on the soft tissues surrounding bone structures and can show, among other things, air embolisms and the trajectories of gun shot wounds through soft tissues. The potential use of MR images to the types of research undertaken by anthropologists may prove to be limitless. Currently, there is little or no material discussing the structures of interest to physical anthropologists that appear on MR images. This study sought to detail these structures in an effort to encourage the incorporation of modern technologies, such as MRI and CT, as data collection tools.

The second research goal was more specific, seeking to test if there was a difference in the frontal sinus morphology of a small sample of identical twins. In this research the frontal sinuses of twins have been described using qualitative indicators as well as quantitative measurements of height, width, depth and volume. These measurements have then been compared to the results of other investigations into the dimensions of the frontal sinuses. In addition, all measurements were duplicated as a simple test of the replicability of the methodology. Because of the small size of the sample, it was not possible to look at differences between the sexes or ages. The results of this study are discussed with regard to the findings of other researchers.

This thesis is organized in a chapter-based format. Chapters Two and Three deal with introductory information. The first background chapter details how MRI works and indicates advantages and disadvantages associated with the use of this technology. The second background chapter discusses the frontal sinuses and details the embryology, development, evolution, function, physical anthropological research on population trends in the morphology of this structure, specific forensic studies on its use in personal identification, and newer research using CT imaging and classification methodologies. Chapter Four outlines the materials and methods used in this research study; it also describes the research sample. Chapter Five addresses the results of the research and contains a discussion comparing these results to those obtained by other researchers. The final chapter presents the author's conclusions, summarises the work attempted by this research, and addresses areas for further or future research highlighted by this project. Appendix One describes forensic case studies where the frontal sinuses have been used to aid in the resolution of personal identity. Appendix two illustrates the screen capture images of the anterior, superior and lateral views of the frontal sinuses for all of the participants analyzed in this study. There is a brief qualitative discussion of the similarities and differences seen in the twins.

# Chapter Two – Background on Magnetic Resonance Imaging

## Introduction:

Magnetic Resonance Imaging (MRI or MR) is an important, relatively new technology that may have many advantages for anthropologists. This imaging modality is extensively used in both clinical and diagnostic fields but, MRI has not been widely utilized by anthropologists to date. In expanding the arsenal of research tools, it is important for anthropologists to recognise and make use of the newest technologies that are available. Working with new technologies, such as MRI, affords us the opportunity to evaluate their potential uses to anthropological questions. Therefore, this study, in its experimental use of MRI on the craniofacial structure and analysis of the similarity between twins, is crucial in evaluating how this new technology could be applied to anthropological problems and research.

This chapter will give a basic introduction to MRI. The history and invention of MRI will be discussed briefly. The chapter will detail in simple terms how magnetic resonance imaging works. MRI has several advantages over traditional imaging approaches; however, there are also several pro and con issues that need to be taken into consideration when using MRI. There are many areas in which anthropology can incorporate MRI and it is important to remember that technologies that are useful in a diagnostic capacity can also be employed to establish personal identity.

## How does MRI work?

Magnetic Resonance Imaging (MRI) is a technique that produces high-resolution and high quality pictures of the structure of any organ or area of the body. The MRI equipment creates a magnetic field, then sends radio waves into the body and detects and measures the resulting response of its cells. From these responses, a computer is able to create a three-dimensional picture of the inside of the body. MRI is utilized primarily in medical and research settings as a diagnostic tool, where it is employed to assist in the identification of tumours, strokes, degenerative diseases, inflammation, infection and other abnormalities in organs and other soft tissues of the body (Imaging Advisory Committee, 2001:6).

MRI is based on the principles of nuclear magnetic resonance, a spectroscopic technique used by scientists to obtain microscopic chemical and physical information about molecules (Hornak, 1996-2003). It was discovered independently by Felix Bloch and Edward Purcell in 1946, who were later awarded the Nobel Prize for their efforts. Primarily, MRI was developed and used for chemical and physical molecular analysis, but by the 1970s it was being applied to detect tumours. MRI is now an indispensable tool for the diagnosis of disease (Schwartz and Huang, 2001:13). MRI was first used as a basic tomographic technique to view images of contiguous tissues. The body is viewed in successive slices of a certain thickness (usually between 5 and 1 mm). This method is equivalent to cutting the image above and below the area to create a slice of information. Each slice is composed of several volume elements, known as voxels. The image is made up of several pixels, or picture elements, which have an intensity proportional to the nuclear magnetic resonance signal intensity of the contents of the corresponding volume element that is being imaged.

MRI is possible because the body contains hydrogen atoms, in the form of water, that act as magnets when the magnetic field is applied. Most clinical MR imaging exploits the use of hydrogen protons as its source of signal because of this abundance of hydrogen atoms in the human body. Approximately 90% of the average human is composed of water which is in turn composed of mobile hydrogen nuclei. The various tissues of the body contain slightly different concentrations of hydrogen protons (see Table 1), these slight discrepancies are enough to produce clear images of the contrasting tissues. Each tissue acquires a high, intermediate or low level of longitudinal magnetization based on the amount of hydrogen proton concentration, resulting in distinct, distinguishable areas on the MR image (Freimarck, 2001:31).

**Table 1**: Relative values of mobile hydrogen concentrations in various tissues (From Freimarck, 2001:31).

| Tissue | Concentration of Hydrogen |
|---|---|
| Muscle | 100 |
| White matter | 100 |
| Fat | 98 |
| Cerebrospinal fluid | 96 |
| Kidney | 95 |
| Grey matter | 94 |
| Spleen | 92 |
| Liver | 91 |
| Blood | 90 |
| Pancreas | 86 |
| Cortical bone | 1-10 |
| Lung | 1-5 |
| Air | <1 |

The principles of MRI are based on the magnetic moment from the nuclei of certain elements. This means that when a magnetic field is applied, the proton or nucleus of that element would align itself with the field. The nuclei do not exactly line up in the direction of the magnetic field, but at an angle to the direction of the field. Each type of nucleus has its own angular momentum. The angular momentum is often likened by physicists to the spinning of a top. If the top is spun at an angle to the vertical, it will rotate on its own axis and the axis of the top's rotation will revolve about the vertical axis. Nuclei are commonly referred to as spin, which can be manipulated to create images (Schwartz and Huang, 2001:14).

If a radio frequency pulse is applied to the proton, the proton will change its alignment so that rather than being aligned with the main magnetic field it will be aligned to the opposite field. Over a period of time, the proton will flip back to align with the field. The process of flipping back to its original alignment will cause energy to be emitted. It is this emission of energy that makes MRI such a useful means to locate and image protons (Schwartz and Huang, 2001:15). A sequence of radio wave pulses is applied repetitively. Each pulse causes the hydrogen nuclei to absorb energy; the nuclei then need time to lose this energy and return to their equilibrium state before they receive the next pulse. The speed of recovery depends on the surrounding nuclei and their movement. This means that the persistence of the signals from hydrogen nuclei in water molecules in different tissues may be different and it is possible to take advantage of these differences to obtain images of soft tissues which have different image contrast characteristics (Feeney, 1996).

The term resonance refers to that property of the precessing nucleus in which it absorbs energy only at a certain frequency. If the frequency is off even by a small amount, the nucleus will not absorb any energy, nor will it change state (Schwartz and Huang, 2001:15).

The magnetic field is a fundamental part of creating the images. The strength of the field must be extremely uniform, or nearly the same at all points in our sample. This is important so that all points in the sample will resonate at the same frequency and produce a high quality image. There are different types of magnets that can be used to create MR images. At the facility where the imaging was being conducted for this research a superconductive magnet was used. Superconducting magnets are commonly used because the magnetic field can be maintained for a long period of time without requiring a constant source of energy; which allows for stronger magnetic fields to be used (> 0.5 T).

The superconductive magnet moves an electric charge that causes a magnetic field to be generated. If the charge moves in a circle, the magnetic field will be produced along a line orthogonal to the circle. This magnet consists of many windings of wire that carry an electric current. The cylinder is typically 55-70 cm in diameter and the magnet is required to be very long to provide a uniform field large enough for imaging.

Enormous energy is required to create and maintain the current to generate the large magnetic fields required for MRI. To reduce the energy requirements superconductivity principles are used. This is a state in which the resistance in a conductor goes to zero at very low temperatures; the temperature is typically very close to absolute zero. To maintain the superconductivity of the magnet the wires are covered in liquid helium. The liquid helium is kept from boiling off too quickly by a Dewar filled with liquid nitrogen (Schwartz and Huang, 2001:18).

When a person is placed into the magnet, the protons line up with the field. There are two possible orientations in which the protons may line up. Ideally all of the protons would want to line up in the same orientation - in the direction of the field - but not all do. While some of the protons will line up with the field, others will line up opposed to the field; most will therefore cancel each other out. The distribution is dependent on temperature and on the field strength. At room temperature, approximately one proton in every million protons will be aligned with the magnetic field, the rest cancel each other out. The excess protons that line up along the magnetic field contribute to our ability to generate a signal and, therefore, an image (Schwartz and Huang, 2001:19).

Net magnetization is created by more protons aligning themselves in one direction than in the other. Net magnetization is the sum of the contributions of all the magnetic moments of all the individual protons and it need not be in alignment with the direction of the magnetic field. In order to create images net magnetization can be manipulated. When a radio frequency pulse at the right frequency is applied the protons begin to change states, or flip to the other alignment. The flipping of individual protons causes the net magnetization to move away from the longitudinal axis. If the RF pulse is of sufficient strength or duration the net magnetization is moved completely from the longitudinal to the transverse plane.

Once the net magnetization is rotated onto the transverse plane, the protons begin to flip back to their original alignment, and the net magnetization vector will return to its initial state along the longitudinal axis. The relaxation of the longitudinal component is called the T1 relaxation, or the re-growth of the magnetization along the longitudinal axis, which is along the direction of the magnetic field. Essentially, this is when the spins or protons are realigning themselves with the magnetic field.

The T1 of protons is different in different tissues in the body. This is the result of the different environment in different tissues at the molecular level primarily the proportion of water that is *bound* in marcromolecules and that which is *free* (in solution). Tissues with a high proportion of bound water, like liver, will have shorter T1. That is, they will relax to equilibrium more quickly than those that have more free water, like fluids which have a much longer T1 (Schwartz and Huang, 2001:22).

The ultimate goal of imaging is to move the magnetization away from the direction of the static field so that we can observe its relaxation (Schwartz and Huang, 2001:24). To change the orientation of the magnetization we must cause it to precess about another magnetic field. An additional magnetic field can be applied with an RF coil at the appropriate frequency. We can control the rotation of the magnetization by manipulating the intensity and duration of the applied RF field. By regulating the signal strength we can create MR images (Schwartz and Huang, 2001:25).

RF coils are an important part of the MRI machine. These coils work like radio antennas to transmit the energy which is used to control the spins and receive the signals generated by the spins as they precess about a static field. A current is passed through the coil to induce a magnetic field; in this way they are similar to the superconductive magnet. A current is also generated in the coil by the precessing magnetization. To image human beings, it is necessary for the coil to be large enough to comfortably hold a person, but the larger the coil the less sensitive a receiver it will be. Similarly, the larger the transmit coil, the more power is required for the same effect inside the subject.

Both the transmit and the receive coils must be orthogonal to the axis of the main magnetic field. These coils must be isolated from one another or the signal to noise performance will decrease (Schwartz and Huang, 2001:26).

While having an MRI examination is not harmful to the person, there are still several precautions that need to be adhered to before the examination takes place. The participant will be asked if they have a prosthetic hip, heart pacemaker (or artificial heart valve), implanted port, intrauterine device (IUD), or any metal plates, pins, screws, or surgical staples in their body. Due to the very strong magnetic fields involved in MR imaging, these types of metal objects could damage the individual. Colour tattoos and permanent eyeliner may cause a problem depending on where they are on the body and what structure is being imaged. It is also important to establish if there are other metal fragments such as shrapnel or bullets; an X-ray may be needed if the patient is not sure. The technologist should be notified about previous surgical procedures. Tooth fillings and braces do not cause harm to the patient, but may disrupt the image. All jewellery, hairpins, eyeglasses, and hearing aids need to be removed before the examination and, depending on the clothing worn by the patient, a hospital gown may be required (Radiology Info - MRI). For the exact procedure employed in this research study, see the Materials and Methods chapter (Chapter Four).

## Advantages

The primary advantage of employing magnetic resonance imaging over all other imaging modalities (such as X-rays and CT scans) is its use of radio waves and magnetic fields rather than ionizing radiation. This point is important on many levels. Firstly, it is beneficial in a clinical study such as this one, where people are volunteering to be research subjects. Ethical considerations of participants' safety are of utmost importance in research, knowing that radiation is not a factor, means MRI is an ethically acceptable way of acquiring information from live subjects. Secondly, in the medical field MRI's reliance on non-radiation based technology means that patients can be monitored before and after treatments. By using magnetic resonance imaging, there is no limit to the number of times that patients can be scanned to confirm that medical procedures were successful or to test new medication.

Both traditional radiographs and CT scans use ionizing radiation. Ionizing radiation causes an atom to become charged. It is produced when an unstable atom decays, releasing energy as ionized radiation. This decay alters the atom's nucleus, since the mass is converted into energy. Ionizing radiation can take the form of alpha, beta or gamma radiation and is known to cause damage to living organisms. Depending on the intensity, duration and target, the cellular damage will vary.

MRI is superior to other techniques, especially X-rays, in gaining access to distinct tissues. By utilizing the water content of hydrogen atoms to construct images, small differences in the water content of different tissues produces pictures with highly visible, discernable structures. In this way, information can be gathered about the health of organs and tissues, in addition to details about their shape and appearance. MRI can detect differences between normal and diseased tissue, and illustrate this in exquisite detail; for example, it is an excellent method for showing the differences between grey and white matter in brain scans and sometimes it can detect damage not visible on other types of scans. Moreover, MRI provides clear images of features inaccessible to X-rays due to their deep location within dense bone structures, which absorb the X-rays and block their imaging. For this same reason it has proved to be the best imaging technique for detecting tumors within the brain stem and for characterizing injuries to the spinal cord. It has become an important tool for detecting brain damage in multiple sclerosis patients and it is now the definitive method for diagnosing this disease (Feeney, 1996).

MR imaging is also advantageous because it offers the researcher or radiologist the chance to view structures in three dimensions. This is a valuable addition over traditional radiographs, where three-dimensional information is obtained through the comparison of lateral and antero-posterior images. This method is comparatively inaccurate compared to the information available through magnetic resonance imaging. MRI traditionally takes slices of the body part being imaged at 1 mm intervals, which provides detailed information on bodily structures. Not only can the researcher acquire information on three dimensions, but this data is available electronically. This means that radiographic films are not produced unnecessarily, and images can be stored indefinitely, without damage or loss to the information, in the computer.

Historically, MRI was a time consuming technique, not as fast as traditional radiographs to obtain images; however, modern innovations in MRI technology permit shorter procedure time and an increased number of scans per day can be conducted (Imaging Advisory Committee, 2001:14). This means that MRI can be an effective outpatient procedure. In this study, the typical time for one scan was six minutes; participants were scanned twice. It was possible therefore, to prepare and image a set of twins in approximately one hour.

## Disadvantages

One of the most significant disadvantages, especially when doing research, is that MRI is expensive. While developments in MRI technology have been made that permit shorter procedure times and thus an increased number of scans can be conducted per day, the relative cost for MRI versus other imaging techniques is still high. In the realm of diagnosis it could be argued that higher costs are negated by a precise and quick diagnosis when first undertaken (Imaging Advisory Committee, 2001:14). But, when it comes to clinical studies it is difficult to acquire enough funding to support the use of such expensive technology as MRI.

Considerations for participant comfort for the duration of the scan are paramount. While it has already been established that MRI is not a harmful technology physically, it can be distressing emotionally. Participants in this study were screened for claustrophobia prior to coming to the clinic. Many papers dealing with MRI consider this to be a shortfall. More modern machines are being developed to deal with this concern. The "short-bore" systems are wider and shorter and do not fully enclose the patient. Some newer units are open on all sides; although the image quality may vary (Radiology Info - MRI). At the University of Alberta, equipment is available, which through the use of mirrors, allows the patient to be able to see out of the machine which reduces the feelings of claustrophobia.

Another, albeit smaller, constraint in using magnetic resonance imaging is that it is not portable. In a hospital setting where patients can be taken to the MRI facility, portability of equipment is not important; however, in a forensics situation where speed and access are often crucial, the lack of portable equipment is a disadvantage. Advances in other imaging modalities have led to portable equipment and it is probably only a matter of time before MRI becomes functionally portable.

Lastly, in the process of carrying out this study it was found that using magnetic resonance imaging can produce image distortion in participants with extensive metal fillings and braces. Metal artefacts, such as jewellery, have to be removed from participants before they enter the scanner; permanent metal fixtures cannot be removed for the scan. The distortion produced by imaging participants with metal in them is immeasurable and in some cases prevents the surrounding structures from being visualized.

MR imaging offers a significant contribution to the medical field and related research work. The advantages of MRI, such as the use of magnetic fields and radio waves, are much safer for patients than the alternative of ionizing radiation. Additionally, the capability to see intricate structures buried deep in dense bone structures aids in our understanding of them and makes diagnosis possible. Moreover, the ability to see these structures in three dimensions and visualize their interaction with other areas of the body electronically is superior to traditional radiographic methods. However, despite all of these advantages there are some difficulties that must be considered. Undoubtedly, technological innovations will lead to improvements in the costs of scanning, portability and patient comfort. Yet, some disadvantages of MRI, such as image distortion associated with metal artefacts, will require more work, or may prove to be unsolvable.

## How is MRI of use to Anthropologists?

Magnetic resonance imaging is a technology extensively used in clinical and diagnostic practice, but not by anthropologists. Several of the advantages of using MRI in medicine are applicable to the research and work of interest to anthropologists. Anthropology can be benefited in many ways and situations by using MRI technology. Traditional X-rays, often used by anthropologists because of their cost-effective, time-effective, ease of use and universality, are well known for the superimposition of structures, which is especially problematic when trying to look at small areas of intricate bone architecture. When using MRI, though, it is possible to obtain images of all internal and external structures without superimposition. This makes it easier for anthropologists to look at structures of the human body such as the inner ear and nasal regions, among others.

Moreover, because MRI works by looking at the water content in different tissues it is possible to get information about not only bone, but also muscle, fat, tendons, ligaments, and air cells. It is important in anthropology to be able to see all of these structures, for example to see the interaction of hard and soft tissues in the knee joint to analyze locomotion. All too often this data is unavailable, but when it is it should be taken advantage of since bone interacts with the soft tissues around it.

The perspective produced by MRI is also advantageous to anthropologists. Magnetic resonance imaging affords the researcher a three-dimensional output with which to consider soft and hard tissues. Contiguous slices are created by the imaging computer which can be viewed successively. This way it is easier to pinpoint the exact level at which certain structures begin and end. This is of particular use for work done on the frontal sinuses where previous studies using radiographically generated data have had difficulty in ascertaining the most inferior point of the frontal sinus, often having to resort to an arbitrary definition of where the sinus starts. The three-dimensional information generated through MR studies means that data can be gained on the depth of certain structures. Information can be stored in computer systems indefinitely for future research and can be accessed an unlimited number of times or by many researchers for comparisons of intra- and interobserver error. While MRI is not the only technology currently available which affords researchers a three-dimensional view of the human body, this form of information is vastly superior to conventional radiographic data.

Lastly, it is important to remember that forensic anthropologists in making comparisons of antemortem and postmortem information are completely reliant on information available from antemortem records. More frequently MRI scans are being carried out on patients admitted to hospitals. Since MRI can be used on a variety of different structures and elements of the body, it is becoming increasingly the technology of choice for a wide range of diagnoses. Forensic anthropologists must adapt to the changes in the medical world to exploit them in the process of personal identification. The only restriction to MRI is water content and it is therefore possible for MR scans to be conducted postmortem. The outstanding detail that can be produced by magnetic resonance images is indisputably helpful in assisting in personal identifications of decedents which cannot have their identity resolved visually.

## Conclusion

This chapter has presented information regarding the use of MRI. It details, in a basic way, how MRI works and its history. It explains the significant advantages to the employment of MRI in both research and diagnostic work. This chapter details ways in which MR imaging is profoundly useful, not only to this research study, but also to medical work in general. While there are many advantages to using MRI, there are also some disadvantages, the chief of which pertains to the cost of scans and equipment, meaning that MRI is not as universally employable as other older technologies such as traditional radiographs. Lastly, information on the specific advantages of MRI to the work conducted in anthropology has been presented.

# Chapter Three – Background on the Frontal Sinuses

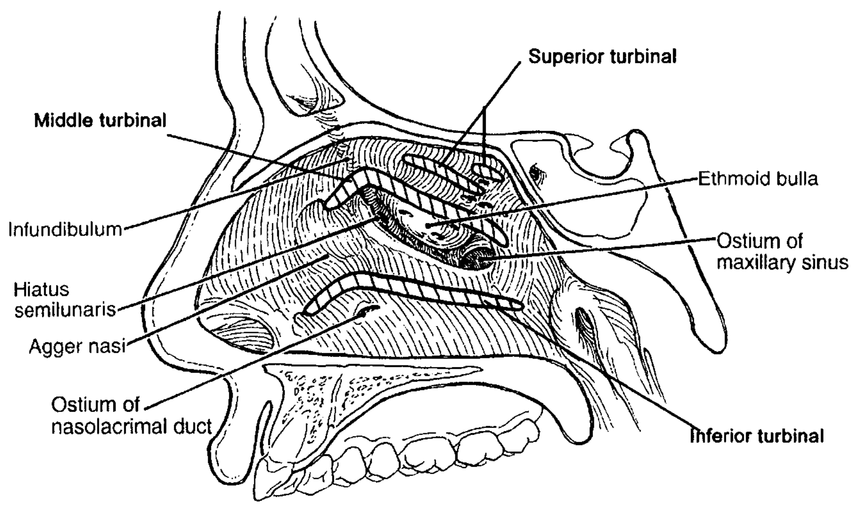
## Introduction

The frontal sinuses, the pneumatic bone structures located between the inner and outer tables of bone in the forehead region, have long been an enigma to anatomists, but for forensic anthropology these structures have played an important role related to the establishment of personal identification. The frontal sinuses are discussed in some of the earliest literature on anatomy. Galen (130-201AD) referred to the 'porosity' of the skull bones, while Vesalius in 1542 described the frontal sinuses by saying they contained nothing but air, and Fallopius in 1600 observed they were absent in neonates (Blaney, 1986:83). This chapter will present an extensive review of the literature on the frontal sinuses, beginning with a brief discussion of the embryology and early development involved in the formation of the frontal sinuses as one of the four paranasal sinuses. The research into the variable forms and different patterns seen in the sexes and populations will be examined. The frontal sinuses are not limited to modern *Homo sapiens* and are in fact seen in several of our closest primate relatives, and this chapter will also include a short examination of the presence and pattern of the frontal sinuses in several of the anthropoid apes. This review will touch upon some of the literature published regarding the possible function of the frontal sinuses. While to date there has been no conclusive role identified for the frontal sinuses, there exists a multitude of potential theories to explain its function. The frontal sinuses have been studied by physical anthropologists, but are more frequently used by those that work in the more specialized field of forensic anthropology. Physical anthropological studies were undertaken in an attempt to uncover patterns based on population affinity, but these early research efforts were largely unsuccessful due to the overwhelming personal individuality of the frontal sinus morphology. Due to observed personal uniqueness, the frontal sinuses have been used to resolve personal identity in many forensic case studies where other methods of establishing identification were not possible. As a result, there is extensive material on how the frontal sinuses have been used to provide a reliable means of identifying human remains in a variety of cases. Lastly, this chapter discusses some of the more recent work being conducted in an effort to create standardized methods for comparing frontal sinus patterns, over basic visual comparisons. Most of the case studies where identity was concluded based on the morphology of the frontal sinuses used traditional radiographs; however, more recently, MRI and CT technologies are being employed for antemortem image capture. Some case studies have made use of these new technologies and these are mentioned because they reflect the way anthropology is embracing new technologies and methods.

## Embryology

The frontal sinus is but one of the four paranasal sinuses, the others being the maxillary, sphenoidal and ethmoidal sinuses (Sperber, 2001:123), and are found adjacent to the nose (Rosin, 1998:3). The frontal sinus forms in two distinct stages – fetally and post-fetally. In the early embryological stage the internal lateral wall of the capsule has three longitudinal ingrowing shelves, one above the other: the inferior, middle and superior turbinals (Figure 1). The middle and superior are the first and second ethmoturbinals. The middle meatus is the space between the maxilloturbinal (the inferior shelf) and the first ethmoturbinal (deBeer, 1985:361). The formation of the frontal sinus begins as early as the end of the third or beginning of the fourth month of embryonic life, with the first step being the extension of the middle nasal meatus in a ventrocephalic direction (Schaeffer, 1920:139). By the fourth month of fetal life the lateral wall of the frontal recess (the mucosa of the middle meatus) has change from being smooth and unbroken to thickened areas of cartilage at certain points. Over time these folds become ossified. Located between the folds are furrows or pits, the positive growth or outpouchings making the folds more prominent. The early expansion of the frontal sinus into the cartilaginous walls and roof of the nasal fossa by the growth of the membranous sac is the primary pneumatization (Sperber, 2001:123). There is considerable variability at this stage with the number of frontal folds and furrows varying from none to four or five (Schaeffer, 1920:140).

**Figure 1:** Sagittal section of the head. Adapted from Donald et al., (1995:44)



The frontal furrows or pits begin to evaginate early and form a set of anterior ethmoidal cells or frontal cells (Figure 2). These cells communicate with the recess. The frontal sinus can be formed in several ways. In the first case the cell enters the frontal bone directly via a wide frontonasal ostium, without the need of a duct; however, if the cell is formed at a distance, in its route of expansion to the frontal bone it has to pass through other cells, being compressed and deformed by the time it arrives. This is how the duct develops as an extension of the original ostium in the nasal wall (Navarro, 2001:85) (Figure 3). Occasionally, the cells originate from the ventral extremity of the infundibulum ethmoidale, either by direct extension or from one of its cellular outgrowths (Schaeffer, 1920:140). Grünwald (1912) (cited in Cave and Haines, 1940:518) adds to this that the frontal sinus is occasionally formed from a groove situated above the ethmoidal bulla but below the middle concha. Navarro states that the determination of which method produces the frontal sinus remains a challenge (2001:85).

**Figure 2:** Illustration of the ethmoidal cells in an adult. Adapted from Weiglein, (1999:46)

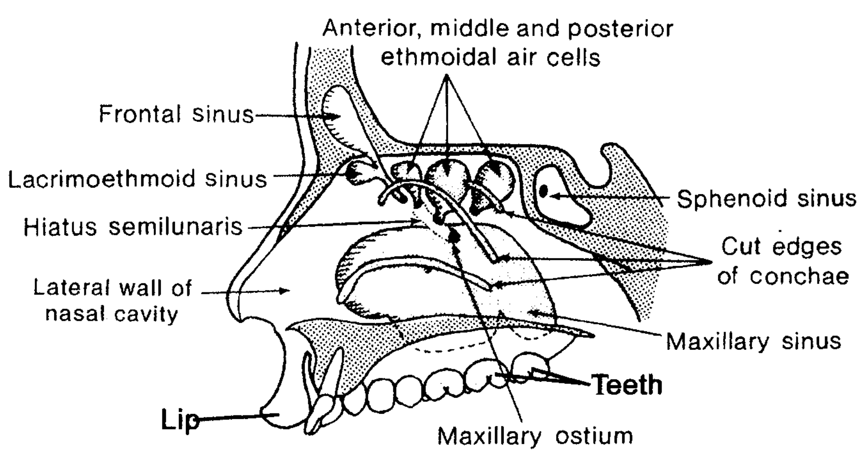
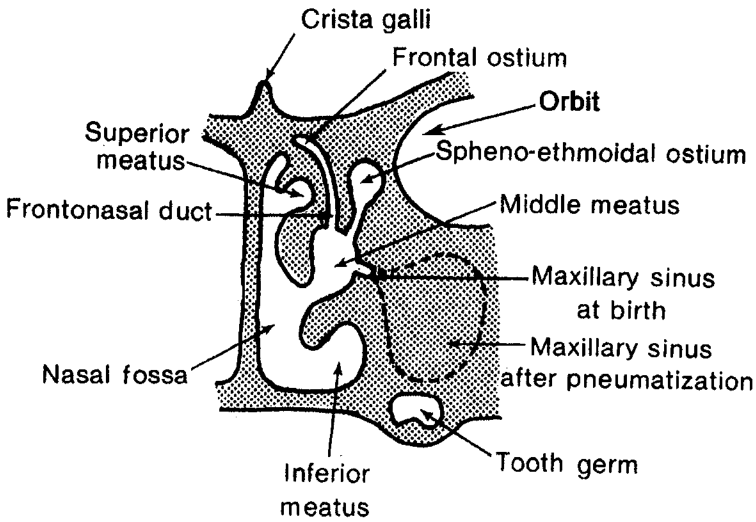


**Figure 3:** Coronal section in development. Adapted from Sperber, (2001:123)




From an embryological perspective, since the frontal sinuses develop variously as a direct extension of the whole frontal recess of the middle nasal meatus, from one or more ethmoidal cells which have their genetic points in the frontal recess, and occasionally from the anterior extremity of the ethmoid infundibulum, it is ethmoid in topography before it ever becomes frontal (Jackson and Coates, 1929:26; Schaeffer, 1916b:238-239). The frontal sinus cannot be absolutely determined until the sixth to twelfth month of post fetal life (Schaeffer, 1920:143).

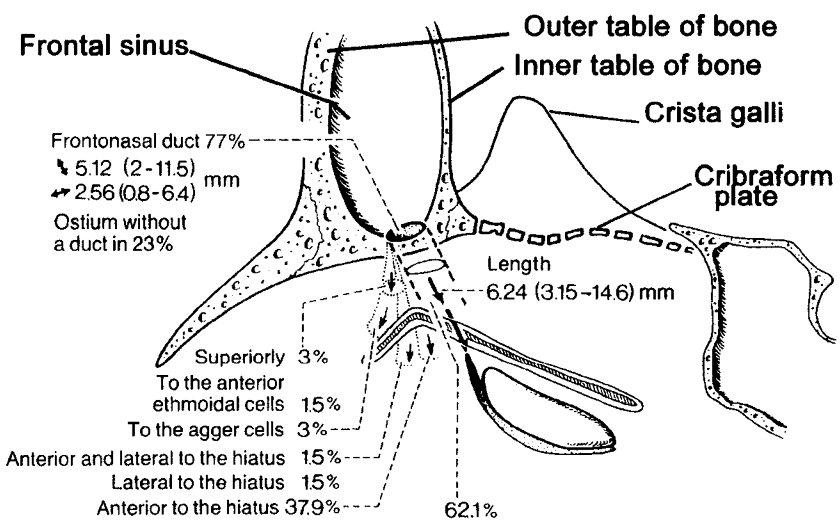
Among the cells initiating the frontal pneumatization, two are basic and give origin to the sinuses, one to the left and one to the right. Other cells in this region may expand, but they are usually small and remain minor. It is important that each cell has its own ostium; otherwise it will be considered an extension of another cell. At the meeting point of the two basic cells with the frontal bone, a main bony septum will remain, separating the right and left sinuses. The position of this septum varies according to the cellular anatomy, the bony resistance to pneumatization, and the air pressure. This septum is seldom situated in the median plane and is rarely vertical, except at its most inferior one third or one fourth, near the base of the sinus. Accessory, partial or incomplete septa may be observed starting at the sinus walls, varying greatly in number, position and dimension (Navarro, 2001:87).

The various outpouchings of the frontal recess continue to grow and extend their boundaries. They start to penetrate into the frontal bone (secondary pneumatization) between six months and two years after birth (Sperber, 2001:124). The outpouchings that form the frontal sinus (if the frontal recess is the origin) ultimately come in contact with the horizontal portion (pars orbitalis) of the frontal bone, between the inner and outer tables of bone. This expansion is made possible by the simultaneous growth of the sinus and resorption of the cancellous bone (deBeers, 1985:361). It should be mentioned that there is a great variation in growth at this stage (Schaeffer, 1920:144). The primary points of outgrowth remain in the adult, although modified as the ostia or apertures of communication between nasal fossae and the sinuses (Jackson and Coates, 1929:14).

By the $18^{th}$ or $20^{th}$ month of life the frontal sinus has begun to ascend into the vertical portion of the frontal bone and by the middle of the third year the cupola of the sinus (a rounded dome forming a roof or ceiling) superior to the level of the nasion. In many cases the frontal sinus never invades far into the vertical portion, but may instead grow extensively into the horizontal portion of the frontal bone to form a large air space(s) over the orbit. Some researchers have defined this lateral growth as an absence of the frontal growth, but Schaeffer believes this is an unjust conclusion (Schaeffer, 1920:145). Scheuer and Black (2000:104) state that sometimes the frontal sinus may penetrate into the crista galli of the ethmoid bone during its expansion. Occasionally, the frontal sinus can extend into the sphenoid, the nasal and the parietal.

The site of origin for each paranasal sinus in the nasal epithelium will also be the place where its drainage ostia will be located. The frontal sinus usually communicates with the frontal recess of the middle nasal meatus, either by way of nasofrontal duct (infundibulum of the frontal sinus) with proximal and distal frontal ostium. Occasionally, the nasofrontal duct or the frontal sinus proper is directly continuous with the infundibulum ethmoidale although, as a rule they are anatomically discontinuous. The various types of communication with the frontal sinuses are illustrated in Figure 4. The drainage ostium of the cell pneumatizing the frontal bone remains at the cell's site of origin; according to Navarro this can be the frontoethmoid recess (47%), the infundibulum (37%), or the prebullar region (16%). The existence, extension and diameter or the drainage duct depends on the pneumatizing cell (Navarro, 2001:87).

**Figure 4:** Various types of communication with the frontal sinus. Adapted from Lang (1989:63)



A variable number of ethmoidal cells may reach the frontal sinus, but only two of them will initiate the sinuses. The others will compete for space, remaining at the base of the sinus or extending elsewhere.

## Development

While the frontal sinuses start to emerge before birth, they continue their development after birth. They are not visible at birth despite the changes that have taken place embryologically. Davis (1918) in his work using 160 dissected crania from individuals aged between birth and 16 years concluded that on the average "the sinus begins its ascent into the vertical portion of the frontal bone during the second year, at three years is 3.8 mm above the nasion, and it continues its vertical advance at an average rate of approximately 1.5 mm/year until the fifteenth year" (Davis, 1918:942). The frontal sinuses grow upward and outward at an extremely variable rate until puberty (Sperber, 2001:124). In his longitudinal study of 100 children, Maresh (1940:76) found that it was hard to pinpoint the exact point when the frontal sinus was developing out of the ethmoidal cells and the individual frontal sinus may not develop at the same time, although one side did not consistently develop before the other. **Table 2** illustrates the dimensions of the frontal sinus at different ages.

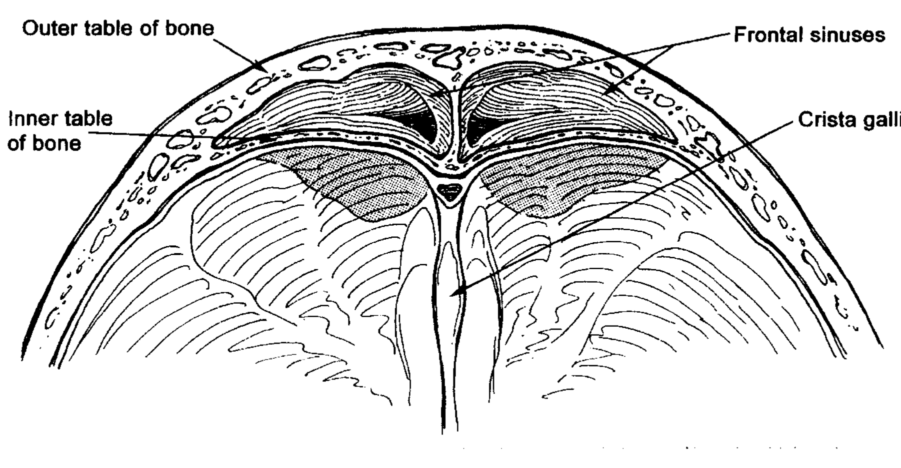
**Table 2** - Size of the frontal sinus related to age, based on measurements in 400 skulls (Adapted from Weiglein, 1999:43)

| Age (years) | Height (mm) | Length (mm) | Width (mm) |
|---|---|---|---|
| 0 | 4-9 | 7-13 | 4-10 |
| 8 | 5-25 | 10-15 | 8-19 |
| 12 | 12-26 | 13-21 | 15-22 |
| Adult* | 24 | 20 | 29 |

* Average

The main enlargement has taken place by puberty. Around this age, for varying periods of from one or more years, there is frequently a quiescent period, followed by a prolonged period of very slow increase in size until the sinus reaches its total enlargement when growth has ceased or temporarily ceased (Brown, 1984:223). Jackson and Coates consider them to have reached adult dimensions by 8 years (1929:26). But Kirk et al. (2002:318) maintain that they continue to grow slowly until puberty, when subsequent rapid growth ensues until they reach their maximum size at age 20. Krogman (1962:278) also believes that the frontal sinuses grow until about the 20th year of life, while Szilvassy (1981) concluded that the frontal sinuses reach adult size at 18 years. Prossinger (2001), through experimental research into the cross-section of the frontal sinus, concluded that growth was far from over after nineteen years of age in both males and females (2001:8). Figure 5 illustrates an example of adult frontal sinuses seen between the inner and outer tables of bone in the axial plane.

**Figure 5:** Adult frontal sinus in the axial plane visible between the inner and outer tables of bone. Adapted from Donald et al., (1995:44)



Jackson and Coates (1929:26) reported the average measurements of the adult frontal sinus as: height 28 mm, width 24 mm, depth 20 mm, volume of right plus left is 14cc (range 1-45cc), Ritter found similar measurement of 28 mm in height, 27 mm in width, and 17 mm in depth (1973:34). While Nambiar et al. (1999:17) found that the height of the frontal sinus ranges from 5-66 mm with an average of 24.3 mm. The anatomy of the frontal sinus remains mostly stable throughout life, although gradual pneumatization can occur through absorption of bone from the inner walls of the sinus through atrophic changes. With increasing age, the walls of the frontal sinus often become thin and the sinuses appear to be larger (Buckland-Wright, 1970:512; Krogman, 1962:278). Occasionally, in advanced age, a continuity with the diploe develops, extending from the supraorbital region to the vertex of the vault (Krogman, 1962:278).

The configuration of the frontal sinus is controlled by environmental factors; gender, race and disease also affect development. Paleopathological changes and trauma are known to modify the form of the frontal sinuses. Young (1951) details just how diseases such as sinusitis can alter the radiographic appearance of the frontal sinus by causing opacity in one or more of its compartments with little or no evidence in the other sinuses. Other diseases such as tumours (both benign and malignant), polyps and osteomyelitis can affect the morphology of the frontal sinuses, altering their radiographic appearance (Young, 1951:214-218). Inflammatory processes such as syphilis and tuberculosis, as well as trauma, can change the appearance of the frontal sinus (Buckland-Wright, 1970:512). Francis et al. (1990) found that there was no statistical difference in the frontal and maxillary sinuses between normal individuals and those with cleft lip and palate. They concluded that "...the difference therefore in air pressure during respiration in cleft lip and palate patients does not seem to alter the pneumatization of the frontal and maxillary sinuses" (1990:922).

Maresh (1940) confirmed Davis' observations and stated that although the frontal sinuses are visible anatomically as early as the first year of life, they cannot be seen radiographically until seven to nine years. Kirk et al. (2002) state that they are radiographically visible at age five years (2002:318) and Navarro (2001) says that by the fourth year they are already radiographically detectable (2001:85). Sperber puts the age of radiographic visibility at six years (2001:124). The degree of individual variation acknowledged by these researchers and others is a possible explanation for the different ages provided for the radiographic visibility of the frontal sinus.

The shape of the frontal sinuses is largely determined by the interaction of 1) endocrinal; 2) mechanical; and 3) other factors inherent in the mucus membranes (Buckland-Wright, 1970:512). The frontal sinus is highly varied in its shape and size, but the most common pattern is asymmetrical and roughly pyramidal (Jackson and Coates, 1929:22). They are normally divided into left and right sides (Scheuer and Black, 2000:104). The neighbouring frontal sinuses frequently trespass on each other and will often alter the position of the septum so that it is not in the midline. The dramatic variation in frontal sinus morphology means that they can be represented by anything from simple chambers to complex subcompartments with recesses formed by incomplete membranes and bony partitions. In a study of 250 skulls, Monteiro et al. (1957) distinguished that 4-8% of sinuses were large, 35-43% were medium and 49-61% were small or absent, although there are no size guidelines provided for these categories (Scheuer and Black, 2000:104). Hajnis and Pozdenova (1972) investigated the form, size and capacity of the frontal sinus in 60 adults from an archaeological collection. They found a large variety of sinuses represented even within a sample this size. Given these findings the authors constructed four groups to represent the morphological variation (Hajnis and Pozdenova, 1972:274). Gulisano et al. (1987) found that there was a correlation between the height and width of the frontal sinus in 520 individuals. They also found that asymmetry was greater in those with a dolichocephalic shaped head.

Szilvassy (1981) conducted a study on a total of 215 children and youths aged 3-17 years (117 boys and 98 girls) to examine the growth rate and difference between the sexes. In his results he saw a profound difference between males and females. The frontal sinuses of girls increase evenly in size overtime, so that from 1-5 years the development of boys and girls is parallel; from 8-12 years the growth rate of male frontal sinuses is very low, causing retardation of growth when boys are compared to girls; after that period a substantial acceleration of the growth rate takes place so that from ages 14-15 years the frontal sinus of males has surpassed that of females in size (Szilvassy, 1981:138). In his study, Brown (1984) found that the growth period for the frontal sinus is shorter in girls, but it is slightly more variable than that of boys. He states that the duration of growth is four years shorter for girls, which might explain why the average height has been identified as 6 mm less in females than males (Brown, 1984:226). Prossinger (2001) found that males and females develop at different rates in the frontal sinus cross-section areas, with females developing more rapidly than males and completing their development much earlier. Harris et al. (1987b) studied the differences in frontal sinus measurements between the sexes and between two races. They measured the perimeter, height, width, total area and interorbital width on the radiographs of 30 males and 30 females of "Black" and "Cape Coloured" populations. They reported that there was a tendency for male sinuses to be larger in size and have more loculations than those of the females (Harris et al., 1987b:54-56). Buckland-Wright (1970:512) also states that the sinuses are generally larger in males, although in females the arcades of the scalloped upper border are smaller and more numerous. This opinion is held by Krogman (1962:278).

Some authors have commented on racial differences. The work mentioned above by Harris et al. (1987:56) found that "blacks" were more likely to have absent frontal sinuses (but it is important to note that the sinuses were only measured as those above the supraorbital line), and a larger interorbital width. Logan Turner (1901) noted the frequent absence of the frontal sinus in Australian Aborigines, while Brothwell et al. (1968) noted the well-developed frontal sinus in "African Negroes". Wolfowitz (1974) suggested that there might be a genetic basis to the diversity of frontal sinus development in different races. The racial differences reported by these authors have led to several physical anthropological investigations into the morphology of the frontal sinus in an effort to racially characterize this feature.

Supernumerary, or extra, sinuses are common and can be found in differing patterns, including side by side in the sagittal plane, over one another in the horizontal plane, or behind one another in the frontal plane (Jackson and Coates, 1929:22). Schaeffer (1920:146) observed as many as six frontal sinuses in one skull and as many as four sinuses on one side. According to Schaeffer (1920:150), unilateral and bilateral supernumerary frontal sinuses are extremely common, occurring in both the vertical and horizontal portion of the frontal bone. He also states that there can be many partial septa present. The supernumerary sinuses come into existence through a proliferation of certain ethmoidal cells between the inner and outer tables of bone on the roof of the orbit. Jovanovic (1961) defines them as completely closed cavities within the bone with their own channels to connect them with the middle or superior nasal meatus. There are various names for theses cells - "cells growing in the thickness of the upper orbital wall", "orbital cells" - although most researchers use the term supernumerary sinuses. Jovanovic (1961:134) agrees with Schaeffer, believing the primary frontal sinus to be at the junction of the vertical and horizontal portions of the frontal bone, whereas any supernumerary sinuses would be located behind or sometimes to the side of this principal cavity.

Some authors have found them to be rare (in 0-10% of cases), but Jovanovic (1961), who seems to have conducted the most in-depth study into supernumerary frontal sinuses, found them in 21% of the individuals he examined. They were situated bilaterally in 16.6% of cases, unilaterally on the left side in 4% of cases, and unilaterally on the right side only in 0.3%. They were found more often in males than females, and more frequently in older individuals than in children. Most frequently there was only one cavity to a side, but the number did vary from one to six on one side. Supernumerary sinuses were usually situated behind the primary sinus and very rarely were cavities of larger dimensions found to encircle the principal frontal sinus. In two specimens they lay between the two principal sinuses in the vertical portion of the frontal bone, but this is a rare anomaly. The supernumerary sinuses grow backwards to sometimes come into contact with the sphenoid sinus. In 4% of cases they come to the very margin of the lesser wing of the sphenoid and in 2% of cases they penetrate the lesser wing and spread to the posterior margin (Jovanovic, 1961: 135-140).

In addition to extra sinuses, it is also possible for the frontal sinus to be completely absent or partially developed. Schaeffer (1916a) noted that even if a sinus may appear to be absent, it is actually only very diminutive; true "agenesis, or absence of the frontal sinus, is very unusual" (Schaeffer, 1916a:667). Absent or hypoplastia is a characteristic of those suffering with Down's Syndrome (trisomy 21) or Apert's Syndrome (acrocephalosyndactyly), but occasionally the condition appears to be unrelated to pathological conditions (Scheuer and Black, 2000:104). Agenesis has been found bilaterally and unilaterally. Boege claims to have found bilateral absence in 4% of 203 skulls examined (cited in Schaffer, 1920:157). Both Turner and Porter noted that absence of the frontal sinuses is more common in so called "mixed races" than "pure ones" (cited in Harris, 1987b:51). Krogman (1962:278) states that in about 5% of adults no frontal sinuses may be observed radiographically; in 1% it may be absent unilaterally (although often the "absence" is due to an extremely deviant septum). Frequently, the frontal sinuses do not make it to the more squamous part of the bone and therefore it is difficult to see them radiographically if they do not develop above the orbits. Many researchers in fact, have drawn a line connecting the superior margins of the orbits and used this as the most basal part of the frontal sinuses. This would lead to a false-positive result of agenesis in some cases. Errors have undoubtedly been made in assuming the frontal sinus is absent in those cases in which there was no pneumatization of the frontal or squamous portion (Schaeffer, 1920:158). Few researchers have commented on what might cause agenesis of the frontal sinus.

Caffey (1967) notes that in three chronic hemolytic anemias of infancy and childhood the bone marrow becomes hyperplastic. This overgrowth of hemopoietic tissue in the skull causes a widening of the diploic space owing to external displacement of the outer table, which also often becomes atrophic. The marrow hyperplasia and internal swelling of the temporal and paranasal bones can cause the airspaces in the temporal bones and paranasal sinuses to be encroached upon and occasionally obliterated (1967:81-83).

Some studies have researched the similarity of frontal sinus morphology between twins. Twin studies focusing on the frontal sinus (Turpin et al., 1942; Schuller, 1943; Asherson, 1965; Dillon and Gourevitch, 1936) clearly demonstrate that although the frontal sinus shows greater similarity between pairs of monozygotic twins than between dizygotic twins, even the former show at least minimal differences. The study by Turpin et al. suggests that the differences seen in the frontal sinuses increased with age, at least until adulthood when growth would be completed. Maresh (1940) found differences in the frontal sinuses of fraternal twins. Asherson's (1965) important summary article found in all of the 74 pairs of twins there was a difference in the pattern of the frontal sinus. Asherson also proposed a system of classification of frontal sinuses in this article and noted that in over 2000 cases he had never found two identical frontal sinus patterns (cited in Quatrehomme et al., 1996). Likewise, a pilot study conducted by Harris et al. (1987a) found that in thirty-two subjects "no two frontal sinuses were alike" (1987a:10) and Camps (1969:155) stated that "the chances of two people having a similar shape frontal sinus is so remote that this method of identification can be safely relied upon".

Some authors in older publications have commented on a relationship between the persistent metopic suture and the absence of the frontal sinus. Brothwell et al. (1968) wrote that the association of metopism with congenital absence, or under-development, of the frontal sinuses is still debatable. Schuller (1943) stated that the belief that metopism accounts to a large extent for the absence or reduction in size of the frontal sinuses is highly debated (cited in Buckland-Wright, 1970:512). Marciniak and Nizankowski (1959) sought to investigate the relationship between the development of the frontal sinuses and the frontal bone. They acknowledge that the development of the frontal sinuses is not directly related to that of the frontal bone since the frontal sinuses form as invaginations. They studied 2,018 patients represented by radiographs and 352 skulls from a museum collection for evidence of persistent metopic suture and frontal sinus absence. The authors concluded given the material they studied that metopism is not associated with the underdevelopment of the frontal sinuses since the absence of the frontal sinus is no more prevalent in skulls with a persistent metopic suture than those without it (Marciniak and Nizankowski, 1959:350).

## Evolution

When examining a particular organ or area of the human body it is useful to consider the same area in closely related species. Often this form of information can result in the discovery of evolutionary relationships between genera. Given the amount of individual variation seen in modern populations of *Homo sapiens* alone, it is uncertain that the frontal sinus could be used to construct phylogenetic relationships between humans and their nearest relatives. Therefore, the purpose of this section is to consider the presence or absence of the frontal sinus in other species and the nature of its morphology, without attempting to construct any evolutionary relationships.

The presence of an ethmoidally-derived frontal sinus is a shared derived character between African apes and humans to the general exclusion of other anthropoids (Vineyard and Smith, 1997:3). True frontal and ethmoidal sinuses however, are confined to the African anthropoid apes and man (Cave and Haines, 1940:498). The absence of a true frontal sinus is a primitive feature in primates and since the ethmoidal sinuses are confined to anthropoid apes, the frontal sinus, as a derivative of the ethmoidal cells, is likewise limited to this group (Cave and Haines, 1940:502). To qualify as a true frontal sinus the pneumatized cavity in the frontal bone must develop from an anterior ethmoidal sinus and open into the antero-superior aspect of the middle meatus. These guidelines were not always so strictly applied and frontal sinuses have incorrectly been described in several genera including *Lemur, Nycticebus, Alouatta* (Seydel, 1891) *Cebus,*(Weidenreich, 1924), *Daubentonia, Hapalemur, Propithecus, Indris,* (Weinert, 1926) and *Pongo* (Cunningham, 1909; Schultz, 1936) (cited in Blaney, 1986:81).

Cave and Haines (1940) commented on the existence of the paranasal sinuses, including the frontal sinuses, in anthropoid apes. They notice that the orangutan has no frontal sinus, and although the frontal bone may be pneumatized this is the result of expansion of the maxillary sinus into the interorbital septum (Koppe and Ohkawa, 1999:111). Chimpanzees possess a frontal sinus that opens into the angle between the ethmoid bulla inferiorly and superiorly the attachment of the ethmoturbinal. In the chimpanzee the frontal sinus is a spherical structure that lies in the upper part of the interorbital septum at the level of the first molar. At this level it rarely encroaches on the upper margin of the orbits. In more posterior CT scans in the region of the second molar, the frontal sinus enlarges gradually in the superior and posterior directions; right and left sinuses can be seen to be divided by a vertical bony septum. The frontal sinus is largest in the region of the third molar with the pneumatization of the browridges, including parts of the orbital roof where a considerable part of the sinus is found (Koppe and Ohkawa, 1999:102).

The frontal sinus of the gorilla has been studied in detail by several authors. The gorilla has a well-developed frontal sinus which is formed by anterior ethmoidal cells and opens similar to the chimpanzee sinus. In the case of the male gorilla, the frontal sinus is large and complicated. There are some differences between the gorilla and human frontal sinuses. Humans have a profusion of ethmoidal cells, which go on to form the frontal sinus, whereas the gorilla never has more than three of these cells. This results in the considerable variation in the exact site of origin, and thus communication with, the nasal fossa. In every gorilla and chimpanzee examined in the study by Cave and Haines (1940), the frontal sinus arose as a diverticulum from the suprabullar groove. This is the rarest form of development in humans, but it seems to be the most frequent, if not only form, in African Anthropoid apes.

Cave (1961) conducted a more in-depth study into the gorilla frontal sinus, discovering that the growth of the sinus was influenced by the eruption of temporary and permanent dentition. He detailed all the stages and their dental associations and found that the sinus is enormous in adult specimens, and generally larger in males than females. In later life there might be some bone resorption in the region of the frontal sinus, but this was rare (Cave, 1961:367).

Blaney (1986), in a more sophisticated study, explored the racial variation between *G. g. gorilla* and *G .g .beringei* and undertook an allometric study to investigate frontal sinus size with respect to body size. Absence was reported to be more common in females than males. The author also found a positive relationship between the volume of the frontal sinus and skull length and detected some racial differences. But, in the chimpanzee sample, Blaney found no racial differences or sexual dimorphism. There was no pneumatization of the frontal bone seen in *P. pygmaeus* (Blaney, 1986:93). This is also reported much earlier by Weidenreich (1943:166).

While there have been some studies on apes, there have been few publications dealing with the frontal sinus of the fossil hominids. Weidenreich (1943, 1951) published two extensive volumes, one discussing *Sinanthropus pekinensis* (now classified as *Homo erectus*) and the other with *Homo soloensis* (now classified as an archaic *Homo sapiens*). In these volumes he briefly discusses the frontal sinus morphology. He found that the frontal sinuses in four specimens of Peking man were "small and strictly confined to the lowest part of the interorbital region". In this same volume Weidenreich compared the frontal sinuses of Peking man to those of *Pithecanthropus erectus* (now also classified as *Homo erectus*). He reported a difference between these two populations, observing a large sinus extending upwards to the glabella and laterally over the medial part of the orbital roof in *Pithecanthropus*, which is also seen in the Ngandong skulls. In the archaic *Homo sapiens* material from the Solo River, Weidenreich saw that the frontal sinus was present in all skulls and recognizable in the skull of a child.

Cunningham (1908), in a lengthy article on Neanderthals published at the turn of the last century, briefly mentioned the frontal sinus. He commented that there was not necessarily a correlation between the degree of development in the area of the glabella and the supraorbital region. He described the frontal sinus in Neanderthals as lying well back and the anterior wall is formed by a thick layer of bone, similar to Australian Aborigines (Cunningham, 1908:305). Blaney, in discussing Neanderthals, noted their exceptional degree of pneumatization, which is also mentioned by other authors (Sergi, 1960; Coon, 1962; Vlcek, 1965). Weidenreich commented on the large size of the Neanderthal frontal sinus (1943:166). Heim (1974) pointed out that the frontal sinus volume in the Neanderthals is directly related to the development of the supraorbital torus; this is unique amongst primates and, more importantly, the hominidae (cited in Blaney, 1986:84). Vlček (1967) (cited in Koppe and Ohkawa, 1999) states that the pneumatization pattern of the frontal sinus of recent *Homo sapiens* differs from that of *H. erectus* and Neanderthals; this is because in the latter two the frontal sinus pneumatizes the supraorbital torus, similar to that of the great apes, however, in modern humans the sinus enlarges into the squama of the frontal bone.

Newer research is being conducted using three dimensional technologies to look at fossil skulls. Using computerized tomography (CT), Prossinger et al. (2000) show that the Petralona skull from Greece (classified as *H. heidelbergensis*) has an enormous frontal sinus with many lamellas or septa interconnecting the outer and inner tables (2000:171). Prossinger et al. used the same technology to show affinities between Steinheim, Bodo and OH 9 specimens (2000:254). Research on the Broken Hill cranium found that the frontal sinus invades not only the browridges but also the squamous part of the frontal bone and is considerably larger on the left than the right side. In comparison to the sinus volume relative to cranial length for modern humans and African great apes, the frontal sinus of Broken Hill was noted to be much larger (Spoor and Konneveld, 1999:211). Rae and Koppe (2004) note that several early Miocene fossil hominoids, including *Proconsul, Morotopithecus, Afropithecus* and *Turkanapithecus*, possess air cells in the frontal bone that closely resemble the frontals sinus of extant African apes. The incomplete preservation of these crania, however, prevents the precise homology of these air cells to be ascertained. CT examination of the stem catarrhine *Aegyptopithecus* suggests this animal may also possess ethmoidal air cells that invade the glabella, a condition homologous with the African apes. This interpretation of frontal sinus homology implies the sinus is primitive for catarrhine (2004:214).

From the sources considered here, it is clear that there is some variation in the frontal sinuses of anthropoid apes and our closest fossil hominid relatives (Table 3). It is clear that both sub-species of gorilla have frontal sinuses, but there is a large amount of variation between populations and the sexes.

**Table 3** - Volumes of the paranasal sinuses of Broken Hill 1, modern humans, chimpanzees and gorillas (from Spoor and Konneveld, 1999:211)

| | N | Frontal | Maxillary | Sphenoidal | Ethmoidal |
|---|---|---|---|---|---|
| **Absolute Volume** ($cm^3$) | | | | | |
| Broken Hill | | 25.63 | 56.47 | 15.69 | 8.06 |
| Modern Humans | | | | | |
| Braune & Clasen (1877) | 4 | 6.1 | 26.8 | 6.7 | 5.7 |
| Bezold (1943) | 102 | 10.5 | 27.8 | - | 7.9 |
| Schumacher et al (1972) | 8 | 7.7 | 18.0 | 6.7 | 6.7 |
| Koppe & Schumacher (1990) | 9 | 6.83 | 24.66 | 9.95 | 6.05 |
| *Pan troglodytes* | 10 | 6.36 | 38.41 | 6.82 | 13.57 |
| *Gorilla gorilla* | 10 | 26.19 | 83.24 | 2.67 | 35.99 |
| **Relative Volumes** * | | | | | |
| Broken Hill | | 13 | 17 | 11 | 9 |
| Modern humans† | 9 | 10 | 15 | 11 | 9 |
| *Pan troglodytes* | 10 | 10 | 18 | 10 | 13 |
| *Gorilla gorilla* | 10 | 11 | 16 | 5 | 12 |

* Relative to cranial length: (cube root of sinus volume/porsthio-opisthocranion) x 100

† Relative values of modern humans could only be calculated for the sample from Koppe and Schumacher (1992).

In chimpanzees, the frontal sinus seems to be more uniformly represented and sexual dimorphism is low or absent. The frontal sinus seems to be absent in the bonobo, but this could be attributable to the small sample sizes. The fossil hominids discussed here all have frontal sinuses to some degree. In the Neanderthals these sinuses are large, but information concerning the exact shape of this area is wanting. Newer research using computerised tomography into other fossil hominid species and more distant relatives suggests homologous structures to the frontal sinus may be present, although this evidence is promising rather than conclusive.

## Function

The true function of the frontal sinus is unknown, though many theories have been proposed. It is important to remember that these theories are not necessarily mutually exclusive and more than one may be correct. One should also bear in mind that these are based on hypotheses that have not been proven to be either valid or invalid. Many of the hypotheses, especially older ones, expounded by the authors and researchers in the literature are based on assertions with little scientific testing behind them, which contributes to the difficulties in concluding the role of the frontal sinuses.

One of the most common proposals for the function of the frontal sinuses is that it imparts resonance to the voice. Halle (1931) noted that the internal periosteum and mucous membrane vibrated with respiration and was more marked when the voice was raised, while Harris et al. (1987b) believe that the frontal sinuses presumably contributed to speech resonance (1987b:51). Negus (1957) found no relationship between the size of the sinus and the quality of the voice. Flottes et al. (1960) believed that the sinuses did not have a phonatory function because they are closed spaces with fixed volumes.

Furthermore, a resonance function is rendered impossible by the location and narrowness of the ostia and the mucous membranes would obstruct vibrations. Jackson and Coates (1929:16) think it is unlikely that the frontal sinuses serve an important influence on vocalization. Flottes et al. (1960) noted that surgery to the sinuses does not affect the voice in any way (cited in Blanton & Biggs, 1969). As difficult as it is to establish conclusively, it is generally accepted that this theory is very unlikely (Blanton and Biggs, 1969:137).

A second theory about the function of the paranasal sinuses is that they exist to humidify and warm inspired air. It has been noted that some air exchange does take place during breathing. Frers (1909) remarked that the principle growth of the sinus occurs after birth when respiration becomes important. Jackson and Coates (1929:16) believe the withdrawal of the olfactory function from the paranasal sinuses in the phylogenic history of humans left only the function of warming and humidifying inspired air seen as air change in the paranasal sinus during respiration. O'Malley (1924) believed that the warming of inspired air was accomplished solely by the nose, while Proetz (1932, 1938) agreed that air did not circulate through the sinuses and therefore, they would be inefficient at providing moisture. He also noted that compared to the volume of the respiratory system, the volume of air that can be accommodated by the sinuses is negligible and there is a sparse blood supply. Lastly, the rigidity of the sinus structure suggests that they are not synonymous or act in an assistance capacity for the respiratory system (Blanton and Biggs, 1969:138-9).

The sinuses have also been considered as a way of increasing the area for olfaction. This idea is generally considered to be invalid because, although growth is taking place during childhood, small children do not show retardation in their sense of smell. Moreover, the location of the frontal sinus does not suggest that this would be the case, since it is positioned above the ethmoid and nasal cavity. Blanton and Biggs (1966:139-140) conclude that there is no evidence to suggest that the sinuses have any influence on the detection of odour. There has been no rigorous testing of the theory that the frontal sinuses have a role in olfaction, yet Blanton and Biggs (1969) state that it is generally believed that these structures do not have a role associated with the sense of smell.

The absorption of shock and the protection the organs of the head is a fourth possible function of the paranasal sinuses. The general distribution around the face is believed to be indicative of the protection function, although this placement only shields against vertical force exerted on the head. Rui (1960) felt that as the sinuses were filled with spongy bone over air, this would reverberate and carry the shock to other parts of the head. However, some animals and humans have no sinuses (Blanton and Biggs, 1969:141), which would seem counterproductive as an evolutionary process in this respect.

Blanton and Biggs dismiss secretion of mucous to maintain the moisture of the nasal chambers as a role of the frontal sinus. They state that this theory is old and generally disregarded since the sinuses contain almost no glandular tissue for secretion (Blanton and Biggs, 1969:141). Blaney later stated that the sinuses contain 50-100 glands compared to the 100,000 glands present in the nose (1990:691) and used this information to support the rejection of this theory.

Likewise, the idea of the sinuses as thermal insulators or "air jackets" for the eyes, pituitary gland and brain is not well supported. The lack of distribution of the sinuses around the head and the variability within a species, especially humans, makes this seem unlikely. Koertvelyessy (1972) in his investigation of the relationship between frontal sinus area and the windchill equivalent temperatures in Eskimo crania found that cold-dwelling populations have smaller mean surface areas than populations living in warmer climates. While he did not rule out the possibility that the frontal sinus played a role in cold adaptation, he believed that multiple factors are involved in the determination of the frontal sinus (1972:170).

Another hypothetical function of the paranasal sinuses is to aid in facial growth and architecture of the skull. Harris et al. (1987b) believed the function of the frontal sinus is to buttress the facial bones (1987b:51), and that the cessation of growth at the start of adulthood provides evidence for this opinion. Blaney's work (1986:94) on the allometry of anthropoid ape skulls suggests a structural role for the frontal sinus and that masticatory forces may link sinus size and diet to impact the architecture of the face. Blaney (1990:693) suggests that craniofacial structure has an influence on the morphology of the paranasal sinuses, while others have suggested that the paranasal sinuses impact the structure of the face by resisting forces acting in various directions because of their distribution over large areas (Demes 1987; Preuschoft, et al., 1997). To aid in facial growth, Ravosa et al. (2000) believe "an extensive frontal sinus can reduce the use of a metabolically costly tissue such as bone" (2000:174). Yet, individuals with one predominant frontal sinus or two very small ones do not show a deficiency or asymmetry in facial growth. It is most likely that the size and shape of the sinuses are a consequence rather than a cause of facial growth, and while these areas are certainly related, the exact nature of their interaction is uncertain (Blanton and Biggs, 1969:143).

The air filled nature of the sinuses provides evidence that these structures evolved to lighten the bones of the skull and maintain the balance of the head. Braune and Clasen (1877) concluded that if spongy bone was substituted for the air in the paranasal sinuses this would increase the volume of the skull by 1%. Extensive sinuses are seen in crocodiles, possibly as a means to aid in keeping the skull afloat. Cave and Haines (1940) in their research into the frontal sinuses of the anthropoid apes see the role as a functional one to lighten the skull (1940:520). Other researchers believe that the musculature of the neck is adequate to balance the head, and if more stability were required changes would be seen in the occipital region (Blanton and Biggs, 1969:144). These adaptations are seen in numerous extinct fossil hominids and extant anthropoid apes (the gorilla, for example).

Marquez et al. (2002) suggest that the paranasal sinuses may play a role in defence against infection. These sinuses are a good area for the production of nitric oxide (NO) gas, which impacts ciliary activity, gland stimulation and behaves as a messenger between the upper and lower airways, selectively reversing hypoxic pulmonary vasoconstriction without causing systemic vasodilation. Nitric oxide also functions in defence, permitting mucus drainage through the ostia into the airflow pathway. These authors go on to suggest that the large paranasal sinuses seen in Neanderthals are the result of the need for large amounts of nitric oxide gas because of the demand imposed by their vigorous way of life (2002:107).

Lastly, it is possible that there is no function of the paranasal sinuses. Some researchers believe that these organs are evolutionary remnants, that they once had a function, which we do not seem to be able to determine, but now perform no role. Their irregularity and variability in modern humans certainly speaks for the sinuses not having a specific function (Blanton and Biggs, 1969:143). The enormous variation that Prossinger found in his work on the frontal sinus cross-section led him to believe that this region was a leftover from evolution (2001:9; Prossinger and Bookstein 2003). Weidenreich states that the frontal sinus is not an "active" but "passive" formation. They represent "void rooms" and are formed where a large incongruity exists between two adjacent systems (1943:165). Negus believed they are "unwanted cavities liable to infection" (1958:350). It is possible however, that since those researching the role of the frontal sinus were unable to find one, they therefore assumed that no function existed and explained away the presence of these structures as evolutionary remnants.

Sato and Satoshi (1970) choose to consider the secondary function of the paranasal sinuses since the primary function remains unknown. The authors consider the secretion abilities and ciliated epithelium of the paranasal sinuses as intrinsic in the secondary function of these structures. With an electron microscope the authors engaged in a biochemical study of the mucous membrane and the enzymes it secretes. They concluded that secretion is a defensive mechanism to protect the sinuses from bacterial and viral invasion (Sato and Satoshi, 1970:527).

It is evident from the above discussion that there is no universally accepted function for the paranasal, including frontal, sinuses. Since many of the theories discussed in the research into the role of the frontal sinuses are without rigorous scientific testing, a more thorough investigation would help determine if and what the role of the frontal sinuses might be.

## Physical anthropology

There have been several studies conducted by physical anthropologists into the frontal sinus. Some researchers interested in population studies have tried to determine a specific morphological pattern to the sinus for a particular population and have encountered moderate success, while others have tried to compare data on several populations. The one recurring problem with the nature of this research is the overwhelming individual variation seen in the frontal sinus morphology.

Much of the research conducted into population specific morphology patterns of the frontal sinuses was carried out early in the twentieth century and the authors performing some of these investigations have used the term "race" to describe certain population groups. Modern studies in physical anthropology do not support the term "race" or derogatory categories to describe ethnic groups; however, the author has chosen to maintain the group names and the term "race" where it is used by previous researchers.

Turner (1901) conducted a well-cited investigation into the morphology of the frontal sinuses. Using transillumination he attempted to compare the dimensions of the frontal sinus in 578 skulls of different sexes and "races". He sought to associate different frontal sinus patterns with the shape of the skull. He concluded that "the sinuses possess no distinctive form or size which is peculiar to any of the great skull types" and that there is no correlation between height and breadth of skull and height and breadth of the sinus (Turner, 1901:99). Turner (1901:100) states that the frontal sinuses are present in all races with varying degrees of frequency and concentrates on enumerating his many statistical findings on the presence and absence of this structure in different populations.

Despite Turner's extensive study into eleven population categories, Brothwell et al. (1968:157) saw a "paucity of data on inter-group differences" and collected information on African Negroes, Australian aboriginals, and European populations. They used antero-posterior radiographs of males only, taking measurements of sinus height, width and volume. They found many variations in these populations, and noted there was more in the African group than the Australian group. They found that the African sample had more cases with larger sinuses, and the Australian group has relatively small sinuses. They also analyzed a small sample of selected fossil hominid skulls and found more variation in this group than the modern samples. The authors concluded that studies on frontal sinus variation in early populations are worthwhile (Brothwell et al., 1968:160-162).

Buckland-Wright (1970) sought to inject a more statistical element into the observations of Brothwell et al. He also took measurements on radiographs: greatest height, greatest width, surface area, and depth and calculated volume; the measurements were used to establish simple indices to try and separate out different population groups. He found some indices were more useful than others, but overall these preliminary findings suggest that indices are an acceptable way of separating out different groups. The results reported by Buckland-Wright seem inconsistent. It appears that he does not apply his indices uniformly; rather he uses some indices to identify members of some populations, while alternatives were more useful in separating other groups. This would seem to be an unsatisfactory methodology and is probably the product of the large amount of individual variation in the sample.

Koertvelyessy (1972) launched the first study into the frontal sinuses of Alaskan "Eskimo" populations. He hoped to determine the influence of environmental (climatic) factors on the frontal sinuses of this population. The sample was made up of six Alaskan "Eskimo" groups and he constructed a thin copper wire frame for scale. He found that multiple factors contribute to the small size of the "Eskimo" frontal sinus, and concluded that it was unlikely that simple adaptation to the cold was the only aspect in the determination of frontal sinus size and shape (1972:170).

Hanson and Owsley (1980) continued the physical anthropology work on climatic influence of Northern populations. Since Koertvelyessy (1972) had confirmed that Alaskan "Eskimos" had small frontal sinuses, these authors sought to investigate if small sinuses were common to Non-Alaskan "Eskimo" populations, attempting to establish the influence of climate and temperature on the size of the frontal sinus. They investigated five measurements: left sinus height and width, right sinus height and width, and the total area on antero-posterior radiographs. No difference was seen in the means of the two populations making up their sample and there was no significant difference between males and females. Interestingly, they report that the frontal sinuses are generally larger in Silumuit males than females, while the reverse characterizes the Kamarvik sample. The large standard deviation of all variables indicates considerable heterogeneity in sinus size among individuals (Hanson and Owsley, 1980:252).

Lynnerup and Homoe (1999) also used material from Northern communities but had a sample size rather larger than others (total 175: 77 male and 98 female). Of this there was some historic Inuit material and some more modern material. These authors found that the mean area size for the Greenlandic Inuit were smaller than the Alaskan area sizes. There was no apparent trend between the Canadian and Greenlandic samples, the Greenlandic males having bigger area size than the Canadian males, but vice versa for the females. Lynnerup and Homoe found significant differences in frontal sinus agenesis between the ancient Greenlandic samples and the Alaskan and Canadian Inuit samples (male $p = 0.03$; female $p = 0.0001$) and between the ancient Greenland and the recent samples, and believe this to be the result of admixture. They also reported significant sexual dimorphism, men having larger sinuses than females. The difference in populations inhabiting more or less cold environments opposes the theory of cold adaptation. Masticatory differences might explain the variation in size seen between the modern and ancient samples, but not between the Alaskan Canadian and Greenlandic Inuit samples.

The physical anthropology investigations into the morphology and size of the frontal sinus in different populations have met with limited success. In all of these studies measurements were taken on plane film radiographs and indices were used to some degree in an attempt to separate the populations. Brothwell et al. (1968) found some population trends, especially commenting on the small frontal sinus size of Australian Aborigines and large size of African Negro populations. Buckland-Wright (1970) continued this work and had inconsistent success with the use of several indices to identify populations. Koertvelyessy (1972), Hanson and Owsley (1980) and Lynnerup and Homoe (1999) have all studied Northern populations with differing results. The impact of cold adaptation on the size of the frontal sinus is certainly possible, but has not been proved by the research conducted by any of these authors. It is likely that the individual variation present and acknowledged by many researchers means that using this area to draw conclusions on population patterns or causes of size is almost impossible.

## Forensic anthropology

Within the realm of forensic anthropology, studies involving the frontal sinus have met with more success. Angyal and Derczy (1998:1089) state that "the most reliable parts of the skeleton for identification are those which are anatomically variable or which exhibit change due to pathological development, trauma, or alterations from surgery", such as the mastoid sinus (Rhine and Sperry, 1991) and the ankle and foot (Kade et al., 1967). Reichs and Dorion (1992) state that "their high frequency of occurrence, individuality and permanence render (the frontal sinuses) highly valuable for identification purposes" (1992:10). The amount of individual variation in the patterns of the frontal sinus means this area is better equipped to characterise individuality rather than groups or populations. And the fact that they are little changed throughout life except for trauma, disease or surgery, makes this region a good candidate for personal identification. Many authors have employed the pattern of the frontal sinus to solve cases where personal identification could not be resolved by other means. Others have used the frontal sinus in conjunction with additional techniques (dental patterns, fingerprints) to resolve identification. Some researchers have gone as far as to describe the "frontal sinus print" and compare its individuality to fingerprints (Murphy et al., 1980). Undoubtedly, all of these studies have proven the power of the frontal sinus in determining identity.

Several authors have reported that no two frontal sinuses are the same. In most cases this conclusion is reached qualitatively through observation of frontal sinuses, rather than by quantitative testing. Kullman and Eklund (1990) set out to test the reliability of radiographs of the frontal sinus for identification purposes and to compare the competence of observers at different levels of training and experience. They acquired radiographs of 72 females and 28 males from the Neuroradiology Department of a Stockholm Hospital, taken years apart. In comparing the size and configuration in 99 pairs of radiographs, two observers matched all of the pairs correctly, while the other observer matched all but one (Kullman and Eklund, 1990:7). This experiment illustrates that large numbers of radiographic images can be matched, even though they were taken years apart, and that there is a high accuracy in matching radiographic images of the frontal sinus.

Jablonski and Shum (1989) state that the frontal sinus morphology is most valid for decomposition, burned, mutilated or skeletonized remains, since this way of confirming personal identity is not dependent on skin and soft tissue information, unlike fingerprints. They also raise the point that in the "comparison of radiographic images for patterns of internal bony architecture and external bony contours (the) potential number of unique points of correspondence between two radiographic images is far greater than for equivalent photographic images" (Jablonski and Shum, 1989:222). This highlights the importance of looking at both internal and external bony features to increase the accuracy of conclusions. These authors state that the "individuality of the "sinus print" has been established beyond reasonable doubt" and because of this uniqueness surgical or pathological changes are not required to confirm positive identification (1989:226).

Schuller stated the details of form, size and field position (of the frontal sinuses) are evident on the X-rays and are consistent over time; this led to the comparison of an earlier X-ray with a later one which is of great importance to forensic medicine and anthropology. Schuller went on to say that it is the "specifically characteristic configurations" of the frontal sinus seen on radiographs that can be used "for the absolute identification of skulls" (cited in Marlin et al., 1991:1770). Radiographs of the skull become increasingly important if other antemortem records are unavailable. Antemortem images provide an objective record of anatomical structures and evidence of pathological conditions, previous trauma, and surgery.

Culbert and Law (1927) are generally cited as being the first to use the morphology of the frontal sinus to confirm personal identification in a forensic case. The disfigured remains of two men were found in the Indus River and fingerprint identification was impossible due to the condition of the remains. An examination of postmortem and antemortem skull radiographs revealed thirteen points of identity in the sinuses; the identification was corroborated by the decedent's dentist. Law (1934:195) believes that the sinuses "furnish the most satisfactory means of identification because of their intricate structure and infinite number of points of comparison". Moreover "while the mastoids alone will establish identity, the possibility of a bilateral mastoidectomy, destroying the evidence, makes the sinuses of more permanent value" (Law, 1934:198).

There are a multitude of published case studies that reflect the power of the frontal sinuses to establish personal uniqueness. These sources have not been included in this chapter due to their abundance (for example, see Stewart, 1979; Atkins and Potsaid, 1978; Murphy and Gantner, 1980, Ubelaker, 1984; Yoshino et al., 1987; Marlin et al., 1991; Owsley, 1993; Angyal and Derczy, 1998; Nambiar et al., 1999). Appendix One details a full account of the research and case studies where the frontal sinuses have been used in forensic anthropology and even in archaeology to conclude identity.

The majority of case studies, in fact all those referred to above, were conducted by comparing antemortem and postmortem images of the frontal sinuses on traditional radiographs. This wealth of data illustrates the huge role traditional X-rays have played in confirming identification. Radiology has played a significant role in the medicolegal investigation and identification of remains subsequent to Roentgen's first report on the effects of X-rays in 1896 (Marlin et al., 1991:1769). From the discussion above it is apparent that most research has been conducted using frontal sinus images captured on traditional plane film radiographs. However, more modern technologies are being increasingly used in the clinical and diagnostic realm (University of Alberta, Department of Radiology, Haglund & Fligner, 1993). Technologies such as MRI and CT scanning are being used more and more by physicians and researchers because of the ability of these technologies to produce three-dimensional images. Computerized tomography is replacing to a large degree the use of skull radiographs (Haglund and Fligner, 1993:711). Therefore, these new technologies are increasingly representing antemortem image data archives (Smith et al., 2002). In order for forensic anthropologists and medical examiners to make use of this information to assess personal identity, the issues associated with these newer imaging methods need to be explored. While there are not many articles dealing with this form of research, some newer publications regarding frontal sinuses as viewed on computerized tomography images can be found (Reichs and Dorion, 1992; Reichs, 1993; Haglund and Fligner, 1993; Smith et al, 2002); however, it should be noted that there is no current research, outside the present study, which looks at the frontal sinus as captured through the use of MRI.

CT is a three-dimensional imaging technique which creates a set of cross-sectional images of the any part of the body. These images are created by several X-ray beams passing through sections of the body from hundreds of angles. A computer reconstructs the X-ray information in slice format (Reichs and Dorion, 1992:2). CT scanning is being increasingly used clinically to locate and assess tumours, intracranial hemorrhage or trauma, aneurysm, arteriovenous malformation, cerebral infarction, abscess and infection, congenital abnormalities, and malformations of the brain, abnormalities of the pituitary, sella turcica and optic nerve, and for the evaluation of postsurgical or radiotherapy changes or surgical planning. It is frequently used over traditional radiology because there is no superimposition of structures. CT is used in the diagnostic of orofacial defects, neoplasms, cysts, fractures, abcesses, for muscle mass in temporo-mandibular joint and condylar problems and in endodontics. Anthropologically, it has been used to study fossil skulls, while in forensics it has been used to study bite marks. Given these properties, CT is an "excellent method for examining frontal sinuses" since it allows for the visualization of internal structures in detail for the assessment of their morphology (Reichs and Dorion, 1992:3).

The studies by Reichs and Dorion, 1992; Reichs, 1993; Haglund and Fligner, 1993 and Smith et al., 2002 illustrate that CT images of the frontal sinus can be used in forensic cases to resolve personal identity where fingerprints, dental or visual identification are not possible. This is important to establish given the fact that computerized tomography and magnetic resonance imaging are quickly replacing conventional radiographs as the technologies of choice in clinical practice. The above research articles and their corresponding case studies demonstrate that some work has been done to establish CT as a technology that can be used in a forensic context to identify and evaluate similarity to ultimately resolve unidentified remains.

To conclude, the morphology of the frontal sinuses has proved useful in forensic anthropology to resolve personal identity in situations were other known techniques are of limited use. The consistency of this structure in adulthood and the number of points of identification make the frontal sinuses a popular means of identifying individuals. The frontal sinuses can be viewed on traditional plane film X-rays and this methodology is well-established and there are many case studies referred to in this section which have compared ante- and postmortem images of the frontal sinuses to confirm an individual's identity. Newer technologies of image capture, such as MRI and CT, are proving more popular in clinical and medical circumstances and are becoming increasingly prevalent in antemortem records. There have been several studies confirming that CT generated images of the frontal sinuses can also be compared to confirm personal identity. As yet, no studies have examined the frontal sinuses on magnetic resonance images.

## Analytical methods

Most of the authors whose articles are cited in the physical and forensic anthropology sections used basic observation to compare ante- and postmortem images, either radiographs or CT images. While this method can produce the sought after results, comparing general aspects of curvature, size and shape of the frontal sinuses to resolve suspected identity in forensics cases, some researchers have been vocal in campaigning for standardized methodology for the analysis of frontal sinus form. One of the most recent and vocal has been A.M. Christensen (2004, 2005a, 2005b), who has brought attention to the reliability and accuracy of standardized methods for anthropologists called upon to give testimony in court. D.H. Ubelaker (1984) was also concerned about this aspect of the work of forensic anthropologists. Christensen states that the accuracy of fingerprint comparison is well known from several studies, but for the anthropologist on the witness stand, there are no acknowledged statistics for the uniqueness of the frontal sinus (2005:292). This section will describe the work of Christensen and Ubelaker who both sought to ascertain the degree of individuality of the frontal sinus. It will also discuss some of the methods advocated by other researchers for the standardized evaluation of the frontal sinus pattern.

Christensen (2004) states that for those dealing with medico-legal issues there is an absolute need for accuracy and standardized methods of measurement. She comments that there is "no established professional standard controlling operation of the technique and no objective determination standard" (Christensen, 2004:430) although several researchers have commented on the uniqueness of the frontal sinus. Currently, the technique used to "confirm or reject a putative identification" is the "simple visual comparison of side-by-side or superimposed radiographs with the consequence of that the final identification decision is subjective and based solely on the knowledge, experience or ability of the examiner" (Christensen, 2004:430). Because there has been no empirical testing of frontal sinus uniqueness there is no available estimate of potential error rate of identification techniques, which is important because the courts have a history of emphasizing this issue (Christensen, 2005a:1).

Christensen published two similar articles in 2005 to try and assess the individuality of the frontal sinus. In these she insisted on the importance of a large sample size, citing that previous authors who have touched on this problem have had small sample sizes, whereas she had over 500 radiographs in her sample, some of them being duplicates rather than copies of the same individual. Tracing the outline of the uppermost border on these radiographs, she digitized the Cartesian coordinates using a software package and then described the pattern of curvature using Elliptic Fourier analysis. This procedure can "fit a closed curve to an ordered set of data points with any desired degree of precision" using "an orthogonal decomposition of a curve into the sum of harmonically related ellipses" (Christensen, 2005b:293). The ellipses can be combined to describe any closed plane curve arbitrarily well. These were used to generate the outlines of the frontal sinus by calculating the x- and y-coordinates around the centroid of the sinus outline. In comparing each individual to every other one, Christensen generated and calculated distances for 126,253 pairs. The average distance between different individuals (978.26) was significantly larger than the average distance between duplicate outlines of the same individual (88.91) and a test of means showed a significant shape difference in the outlines of frontal sinuses of different individuals (Christensen, 2005b:294). When comparing some different individuals she found that their distance was smaller than the distance produced when comparing replicates from the same individual, but she emphasized the small overlap. She found that the probability of finding a different individual with an Euclidean distance less than or equal to that case's is very small illustrating that each individual's frontal sinus outline is distinctly and quantifiably different at a highly significant level.

Ubelaker (1984) conducted his own study using 35 frontal radiographs of American Indian and Eskimo crania randomly selected from those on file in the Department of Anthropology, National Museum of Natural History/National Museum of Man. He compared each radiograph to every other radiograph in the sample to assess the number of differences in the frontal sinus itself and in its relationships to surrounding skeletal structures. Ubelaker defined a difference as "any detail of the frontal sinus, orbits, frontal crest or related structure within the area showed that was present on one radiograph and not on the other". In complicated sinuses with intersecting borders, a difference constituted a line (usually curved) defined from the points where it intersected with another line or shifted in direction. This is obviously a conservative system because there are an infinite number of points that characterize each line. In 595 comparisons, Ubelaker found that there were at least three differences in every comparison, the number of differences in each comparison ranged from three to fifteen with an average of eight (S.D. 2) (Ubelaker, 1984:406).

Yoshino et al. (1987) attempted to form a classification system of frontal sinus patterns to establish a systematic method of personal identification. They used 35 Japanese skulls (21 males and 14 females), measuring the area of the left and right sinuses to create an asymmetry index (1987:290). They established a classification system based on several categories (area size, bilateral asymmetry, the superiority of side, the outline of the upper border left and right side, presence of partial septa and the supraorbital cells). Each of these categories was subdivided and given class numbers, which were ultimately combined to produce a seven-digit number (Yoshino et al., 1987:294). This number would characterise the frontal sinus of an individual and these numbers once generated for antemortem and postmortem antero-posterior radiographs could be compared.

Reichs and Dorion (1992) and Reichs (1993) use similar characteristics to Yoshino et al, but their articles go into much more detail about the scoring system. They assign numbers based on bilateral dimension, bilateral asymmetry, superiority of side, distribution of partial septa, number of partial septa, distribution of complete cells, and the number of complete cells with 5, 6, 4, 8, 8, 8, and 8 possible class numbers respectively (Reichs and Dorion, 1992:3,5). While Yoshino et al. (1987) evaluated the seven class numbers on antero-posterior radiographs, Reichs and Dorion and Reichs, use a series of contiguous transverse slices produced by computerized tomography scans. Therefore, they suggest evaluating the seven categories on two or three levels throughout the frontal sinus, which would produce a 14- or 21-digit number respectively. If three levels were used this could produce over 118 quadrillion serial combinations of digits (Reichs and Dorion, 1992:5). In this way the class number results of different researchers can be compared simply.

Ribeiro (2000) agrees with Christensen (2004), stating, "...identification is still hampered by the lack of a standardized method of measuring the variables" (Ribeiro, 2000:28). Ribeiro constructs a sophisticated system of measurement, including provisions for "normal anatomy" and "variations in anatomy". For normal frontal sinuses he suggests the measurement of four variables: the diameter of the frontal sinuses, the distance between the highest points of the left and right sinuses, the distances between lateral limit of the right sinus and the highest point of the right sinus, and the distance between the lateral limit of the left sinus and the highest point of the left sinus. In measuring frontal sinuses that do not fit the classic architectural pattern, Ribeiro developed nine rules. The author states that because this technique measures distances it corrects any possible distortion caused by improper positioning of the skull for X-ray (Ribeiro, 2000:28). With the assistance of a computer program, Ribeiro was able to retrieve radiographic images and compare them visually with 100% accuracy (2000:32).

Similarly to Ribeiro, Kirk et al. (2002) use measurements to match antemortem and postmortem radiographs. Digital tracings were made of the frontal sinuses from both sets of images using Adobe Photoshop. These were examined and superimposed, with those that could be superimposed considered to be a "pattern match". In addition, the number of loculations on each side of the septum, the septum deviation, side dominance and pathology were recorded. Maximum horizontal and vertical distances were documented for each sinus. If the difference between antemortem and postmortem values was greater than 5 mm this was considered a "metric nonmatch". If the entire perimeter of the antemortem and postmortem sinus shadows was within 5mm when superimposed, this was defined as a "metric match". Kirk et al. tested this method on a sample of 35 cases consisting of both males and females, ranging in age from 20 to 80 years from the Chief Coroner's Office in Toronto. Kirk et al. report that in all 35 cases it was possible to superimpose the antemortem and postmortem tracings, and using sinus height and width it was possible to match 16 cases (or 46%) (2002:320).

The realisation of a standardized method to assess the similarity of two sets of frontal sinus images would mean that the observation of different researchers would be more easily comparable. Moreover, it would provide added credibility to this method of affirming personal identity in courtroom situations. Several authors have come up with equally good approaches, any of which could become a standardized method. While Ubelaker and Christensen have sought to find out exactly how unique the frontal sinuses of different individuals are, others have created novel systems to match existing images. Despite these articles, most researchers still rely on simple observation to evaluate the similarity of two images.

## Statistics

As an important aside it is interesting to consider how many forensic cases are resolved by the comparison of frontal sinus patterns. Marlin et al. (1991) state that there are substantial numbers of skull radiographs available; based on a survey of a small hospital radiology department, it was found that 2,400 radiographic examinations were made each month for various reasons and that 1 in 25 antemortem films showed craniofacial structures of potential value in identification (Marlin et al., 1991:1771). At the University of Alberta, Department of Radiology, there were 15,150 MRIs and 36,273 CTs conducted in 2004. For the City of Edmonton there were 37,804 MRIs and 102,341 CTs performed. The extent to which sinus configuration is actually employed in the identification of remains is unknown, but it appears that radiographs of the skull may be underutilized as a source of antemortem records (Marlin et al., 1991:1770). There are no direct statistics for how often this frontal sinus comparison is used above comparison of DNA, dental radiographs, fingerprints or radiographs of other areas of the body. Murphy et al. (1980) found in a 15-month study of the City of St. Louis Office of the Medical Examiner that radiological identification was three times more effective than fingerprints and five times more effective than dental methods.

## Conclusion

Anatomists and some anthropologists have acknowledged the uniqueness of the frontal sinuses for a long time. Some researchers have even attempted to quantitatively assess their individuality. This chapter has sought to explore all aspects of the frontal sinus in the literature. The development and embryology have been studied extensively, and we know much about their form and shape manifestations. Many authors have looked at the differences between males and females and the changes that occur with aging. Other anthropologists have discussed the incidence of the frontal sinuses in species closely related to humans (anthropoid apes, fossil hominids). It is clear that "true" frontal sinuses are limited to African anthropoid apes and its appearance in the evolutionary record is linked with the appearance of the ethmoidal sinuses. Despite all this knowledge about the frontal sinus, their function is still not understood. There are several theories put forward to account for the frontal sinus, but none of these has been absolutely confirmed or disproved to date. Frontal sinuses have been analysed both within the context of physical anthropology and forensic anthropology research. Physical anthropologists early on attempted to use the frontal sinus to characterize population groups, but this pursuit was largely unsuccessful, probably due to the high degree of individual variation seen in frontal sinus morphology. Forensic anthropology studies, capitalising on this uniqueness, were more successful and there is an extensive record of frontal sinus morphology being used to resolve personal identity. Largely, all the research concerning the frontal sinus has been conducted using antero-posterior radiographic films; however, some more recent studies have investigated the morphology of the frontal sinus on computerized tomography slices. No one to date has looked at this structure using magnetic resonance images. Lastly, the majority of frontal sinus comparisons are carried out by subjective observation; some recent authors have sought to create a standardised method to evaluate the morphology of the frontal sinus. Several methods have been invented, but none have been put into widespread use.

# Chapter Four - Materials and Methods

## Introduction

This chapter deals with the materials and methods used in this research, and outlines how the participants were acquired for the study and the measures that were taken to ensure their safety. It will also include a basic profile of the volunteers, including their ages and sex.

The twins used in this study were known to the investigation because of a prior request for zygosity testing at the request of the subjects themselves or their families to find out whether the twins were identical or fraternal. Therefore, it was known that all the subjects involved in this study were monozygous or identical twins. The participants were contacted via telephone to ask if they were interested in taking part in this research, which would include a voluntary MRI scan. All participants were told about what would happen if they agreed to volunteer. Those that agreed were given a standard preliminary screening for the MRI procedure, including inquiring if they had any colour tattoos, piercings or had undergone surgery. Due to the very large magnetic field involved in NMR imaging, these necessary precautions allowed the identification of any patient characteristic that could pose a risk during the scanning procedure. MRI appointment times were booked with the MRI technicians and arrangements made for the volunteers to come to the clinic.

At the arranged appointment time, participants were met and taken to the MRI clinic. Before the volunteers signed any consent forms the process was reviewed again to make sure that they understood the whole procedure, and to provide them with an opportunity to ask questions. At this point the volunteer was asked to read and sign the consent forms, which included filling out the MRI procedure and safety checklist. This checklist makes sure that the participant does not have any item in their body that would interfere with the MRI procedure and potentially cause harm. This checklist is reviewed with the MRI technician and the author to ensure correctness and as a double check for safety. Volunteers were asked to remove all metal articles that could be removed, such as earrings and necklaces. Participants were then taken into the MRI facility, where they were shown the MRI machine and the control room, and to familiarize them with the scanning environment. This was done in part to reduce or remove any anxiety for volunteers who had not undergone scanning before.

At this stage participants' faces were marked with a fine-pointed felt tipped marker with water soluble blue ink at the 27 craniometric points being used by other researchers in the study group. The average size of each mark was less than 1 mm in diameter. Next, petroleum jelly was applied with a Q-tip onto the blue marks to act as an adhesive for the gadolinium/agarose beads. The purpose of these beads was to provide a means to detect the anthropometric points in the generated images. The participant was given foam ear plugs to use during the scan to reduce the sound levels associated with the equipment, and they were asked to take off their shoes and lie on the MRI table. The beads were placed on the participant's face once they were lying in position on this table. All the beads were checked again to make sure that they were in the correct position before the researchers and the technician left the room.

The gadolinium/agarose beads were made from a recipe that incorporates 0.5 ml of gadolinium into a solution of agarose followed by the addition of water. The agarose solidifies the solution, making the beads rigid enough to be placed onto the face. Gadolinium was used in this study, and is in fact used widely in MRI studies, because it has a high magnetic moment, which makes the bead show up clearly on the images. The 27 anthropometric points can then be located on the images by finding the bead.

Ear pads and a plastic frame positioned above the face ensured that the volunteer remained as stationary as possible during the scan and the participant was given a hand operated call bell for the duration of the MRI scan, allowing them to alert the operator at any time during the procedure if they became uncomfortable or alarmed, permitting the procedure to be stopped. The researchers and the MRI technician left the room at this point to go to the control room to start the scans.

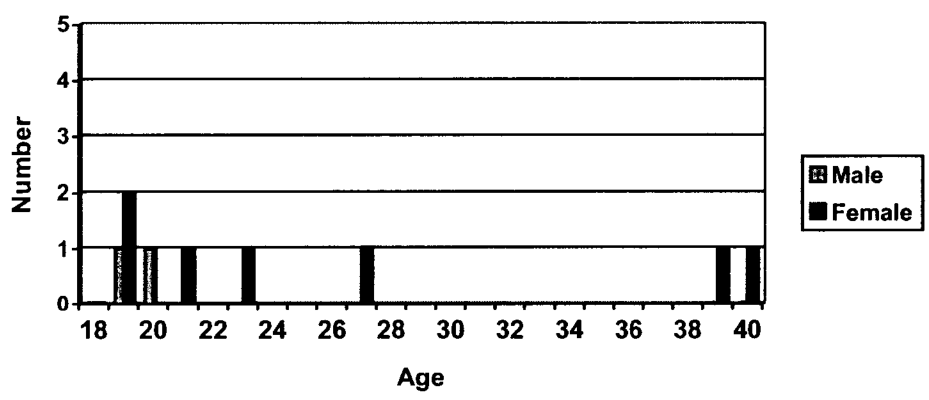
Two scans were performed on each participant to provide data to test the replicability of MRI under these research conditions. The average duration for each scan was approximately six minutes. During the procedure the participant could communicate with the technician via a microphone and the emergency button. Likewise, the technician could communicate with the volunteer. The participant was required to keep very still for the duration of the scans to minimize bead movement and to ensure the highest quality images possible. With MRI technology, even the slightest movements will cause the whole image, or part of it, to be blurry. In addition to testing the replicability of MRI, the second image served as a back up in case movement induced distortion occurred in the first scan.

The only significant causes for participant discomfort were claustrophobia relating to the proximity of the MRI machine components to the volunteer, and the noises during the scan. Participants were required to have their eyes closed for the duration of the scans to support the beads placed on the endo- and exocantion points, a requirement that actually counteracted some of the feelings of claustrophobia. In an effort to minimise the noise, participants were supplied with earplugs and sponges were placed over the ears after the beads were put on the face. While this did not completely eradicate the noise, it reduced it to a more comfortable level.

## The Research Sample

In total there were nine sets of twins in this research set, seven sets of females, and two sets of males. The volunteers in the study were all over the age of 18 years to meet the ethics requirements of the University of Alberta's Arts, Science and Law Research Ethics Board. The youngest individuals were aged 19 years and the oldest set was 40 years (Figure 6); the mean age was 25.2 years. All twins used in this study were identified as being of Caucasian ancestry. All scanning was conducted at the University of Alberta research MRI facility on a 1.5 Tesla Siemens Sonata machine, during the summer of 2004.

**Figure 6:** Age distribution of volunteers by sex



Once the scans were completed, the technician and the author entered the MRI room and the MRI table was taken out of the machine. The plastic frame was removed by the technician and the author removed the beads while the participant was still lying on the table. Once all the beads, sponges and ear plugs were removed the table was lowered and the volunteer was instructed to slowly sit up. The participant was given a moist towel and directed to a mirror so they could remove any remaining blue ink from their faces. A researcher showed the participants out of the MRI facility once they had collected all of their belongings.

Images were saved from the control room computer onto a compact disc, one disc for each set of twins. The twins were identified on each CD along with the date the scans took place. The data was transferred onto the network, and from the network onto the Sun System computers in the Data Analysis room of the facility. This was for backup purposes.

## Data Analysis

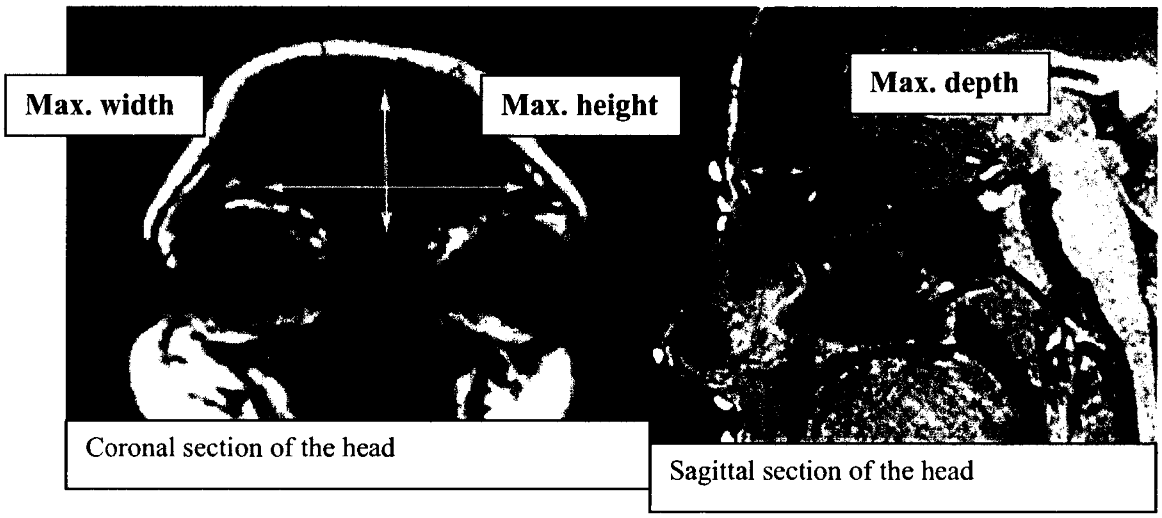
While it was possible to look at the images in the Research MRI facility in the basement of the University Hospital, the equipment in this facility was slow and inferior to the computers in the Department of Radiology. Therefore, the compact discs with the individual twin data on them were loaded onto the computer in the Radiology Department at the University of Alberta Hospital. This was done by a radiologist, Dr. Michelle Noga. Once all the images were loaded onto the computer they were locked to prevent them from being accidentally deleted or edited.

The research goals of this project were twofold. Firstly, the images were reviewed to gain general and anecdotal information about a number of structures useful to anthropologists that appeared on the MR images. Secondly, the frontal sinuses were examined specifically. The frontal sinuses were analysed both qualitatively and quantitatively. Qualitative evaluation can be conducted by describing the observed attributes of the sinuses. This information aids the numerical evaluation by providing a more complete account of the morphology of the frontal sinuses and can be used to evaluate similarities and differences between the twins. Qualitative observations were carried out on images and the frontal sinuses were analysed using verbal descriptors under seven categories – overall shape, presence of the intersinus septum, presence of partial septa, if the intersinus septum was centrally located, whether left of right sides were largest, if one side persisted superiorly over the other, and any other comments.

Quantitative measurements were taken for maximum height, width and depth as well as for volume on the frontal sinuses. The measurements of height, width and depth were conducted separately to volume and were taken first. The radiologist transferred the images of the frontal sinuses from the workstation computer to the Picture Archival Communication Systems (PACS), and was done so that it was easier to view the frontal sinuses and take measurement data.

Maximum height, width and depth were taken by two observers, Dr Noga (an experienced radiologist) and the author. Once the images were transferred onto the PACS each individual file was opened. Measurements were taken by right clicking and selecting the ruler icon, then clicking on the image and measuring the sinuses. The right and left sinuses were included as one entity. The maximum height was usually taken on coronal images, the width was taken on coronal or axial images and the maximum depth was taken on the axial or sagittal images (Figure 7). Often it was necessary to repeat measurements to verify that the maximum dimension was being measured. The radiologist rounded the measurements to whole numbers (in mm), and this procedure was repeated by the second observer for comparison.

**Figure 7:** Illustrations of how volume measurements of maximum height, width and depth were taken




Computations of volume were done on the workstation computer in the Department of Radiology using the GE Advantage Windows 4.2. The images were opened in the Volume Viewer. The volume of the frontal sinuses was taken by the author twice for each twin to establish the repeatability of the experiment.

The acquisition of volume data was made easier by the initial use of three-dimensional technology. Once a participant's images were opened, the volume was taken by clicking on the "3D tools" icon and selecting "paint on slices". An outline of the frontal sinuses was drawn on each axial slide from the inferior part of the sinus to the superior portion. In some volunteers it was difficult to isolate the exact point at which the frontal sinuses started; in some individuals the frontal was continuous with the ethmoidal sinuses. The outline was acquired by holding down the "shift" key while tracing the outline of the sinus with the mouse (Figure 8). The left and right sinuses were measured together as the images were not of a quality that could permit them to be separated. Once an outline was drawn on each successive slide that the frontal sinuses appeared on, the "apply" button was selected. This button instructs the computer to compile all the outlined sections together into a model of the frontal sinuses. To acquire the volume the "display tools" icon was selected and the "sphere" tool was chosen. Then the model of the frontal sinuses was clicked on and the volume was displayed and recorded by the author. This process was repeated. Both models of the frontal sinuses were saved. In addition, and for illustration purposes (see Appendix Two), screen capture images were taken of the models in anterior, superior and lateral planes.

**Figure 8:** Illustration of how volume measurements were taken

Quantitative measurements of maximum height, width and depth and volume were analysed using basic statistics. The measurements of maximum height, width and depth of observer one were compared to those of observer two using a paired T-test statistic to see if there was a statistical difference between these measurements. Likewise, the two sets of volume data were compared using a paired T-test. To test if a significant difference exists between the twins a Chi squared test was constructed. Lastly, to test if there was a correlation between the variables of height, width, and depth

$r^2$ tests were constructed in SPSS. The resulting analysis of this data, and the discussion of the findings, is presented in the next chapter.

## Conclusion

This chapter has reviewed the material and methods used in the data collection and analysis for this research study. It has detailed the research sample and procedure involved in collecting the primary data. This section also discusses the methods involved in testing which structures of use to anthropologists are visible on the MR images and how the morphology of the frontal sinuses was analysed both qualitatively and quantitatively. Additionally, the basic statistics used in this study to compare inter- and intraobserver differences as well as the twins to each other are mentioned.

# Chapter Five - Results and Discussion

## Introduction

It has been established that anthropologists have been using the frontal sinuses as an individualising feature to establish personal identity in forensic situations; however, little has been written about this structure in twins. Since identical twins are genetically the same, any differences seen in the morphology of the frontal sinuses should be the result of environmental factors. The frontal sinuses have never been analysed on magnetic resonance images. This technology is relatively new, and with computerised tomography, becoming the technology of choice for imaging the head and neck. This means that CT and MR images are being increasingly generated and are providing forensic anthropologists with a different antemortem record from traditionally used x-ray images. Magnetic resonance imaging is a relatively new technique that has been used extensively in the medical field and in clinical studies. MRI has several advantages for living patients. Firstly, it uses strong magnets and radio waves to create images of the body, which do not rely on potentially harmful ionizing radiation. Additionally, MRI, because it measures the amount of hydrogen atoms in tissues, produces better images of soft tissues and medical ailments such as brain tumours and joints. Lastly, MRI produces a series of contiguous images that can be compiled into three-dimensional representations. This allows structures to be located and examined with the benefit of three dimensions to increase precision.

To test the use of magnetic resonance imaging to anthropological questions and to examine specifically the frontal sinuses of monozygotic twins using this technology, this thesis project was initiated. This chapter deals with the results of this study. First, the impressions on the usefulness of MR imaging techniques to anthropological research on the head will be discussed. Next the results from the analysis of the twins will be described. These results are both qualitative and quantitative in nature and both will be detailed. Lastly, a discussion of the meaning of these results and a comparison to previously conducted work is presented.

## MRI section

This first section will discuss and detail the application of the MR image data obtained to research questions that are of interest to physical anthropologists. Typically, physical anthropologists study the human body and its form in a pursuit of a better understanding of modern human variation. They are also concerned with the development and distribution of that form, and so many study human evolution. Three-dimensional non-invasive technologies such as computerized tomography and magnetic resonance imaging are being used of late to study fossil human remains as a way to look inside these specimens without causing damage (Rae & Koppe, 2004). Forensic anthropology, as a sub-field of physical anthropology, concerns itself with personal uniqueness in an effort to resolve identity for recovered human remains. In this way forensic anthropologists use specific structures that are known to be unique to the individual to establish the identity of the decedent. There are a number of structures that can be used for this process depending on what is available from the human remains. In some instances, the facial structure of the deceased can be compared to antemortem photographs. Known fractures of specific portions of the body that have occurred as a result of trauma or disease can also be of assistance. Often an antemortem record of the suspected individual is looked for and identity is based on located medical images. Head scans are often taken for trauma or in the case of MRI where a brain tumour or other soft tissue abnormality is suspected. In this way MR images of the head and neck are often available as antemortem data.

The magnetic resonance images used in this study are magnetization prepared rapid gradient echo (MP-RAGE) type. There were two scans taken of each individual in research group and there were a total of eighteen volunteers that took part. The scans themselves are made up of a series of approximately 150 to 200 contiguous images of slices of the head. These images can be viewed in the sagittal, coronal and axial planes. The images are T1 weighted, meaning that fat will show up white and bone will show up black.

Various structures that would likely be of interest to physical anthropologists were clearly represented on the MRI scans collected in this study. At the base of the head and top of the neck the superior cervical vertebrae were visible. The mouth, including aspects of the dentition, tooth roots and tongue as well as the mandible (especially the condyles) could be seen. The structure of the ear was clearly visible on the MR images, comprising of both the inner ear and outer cartilage portions. Along with the frontal sinuses, the other paranasal sinuses (ethmoidal, sphenoidal and maxillary) could be seen on the MR images. The ethmoidal sinus was particularly clear and in most instances the crista galli could be easily visualized as a bright white bulbous formation. Muscles of the neck and dentition could be seen, as could the arteries of the neck, which show up bright white on the MR images. The nasal septum of the nose was clearly visible and is a feature sometimes used in physical anthropology for assessing personal identification.

The nasal bones were visible. These are tiny bones but their morphology related to trauma could possibly used to individualize persons. The eyes and associated structures, such as the optic nerves, lenses, and blood vessels, were exceptionally clear. Brain structures such as the brain stem, cerebellum and lobes of the brain show up well on MRI, and this technology is often used to diagnose anomalies in these areas. Below are several illustrations of the structures that appear on MR images (Figures 9 and 10). These are but some of the structures of the head and neck that are visible using MR imaging that might be of interest to physical anthropologists.

The sheer numbers of structures that are discernable on the MR images collected in this study illustrate the utility of MR technology to study the human head. Anthropologists interested in comparing the form of these structures could make use of magnetic resonance technology to gather data. Additional to collecting information on bone structures, MRI could be more useful to anthropologists interested in studying soft tissues. Fat, cartilage and muscle tissues show up well on T1 weighted MR images. This could be used to study the size of muscles for evolutionary significance, for example. In this study, scans were only conducted of the head and superior portion of the neck. If full body scans were carried out there would be an abundance of structures that would and could be of interest to anthropological research, thus illustrating the importance of this imaging technique to anthropologists.

**Figure 9:** Illustrations of axial sections through the head and neck

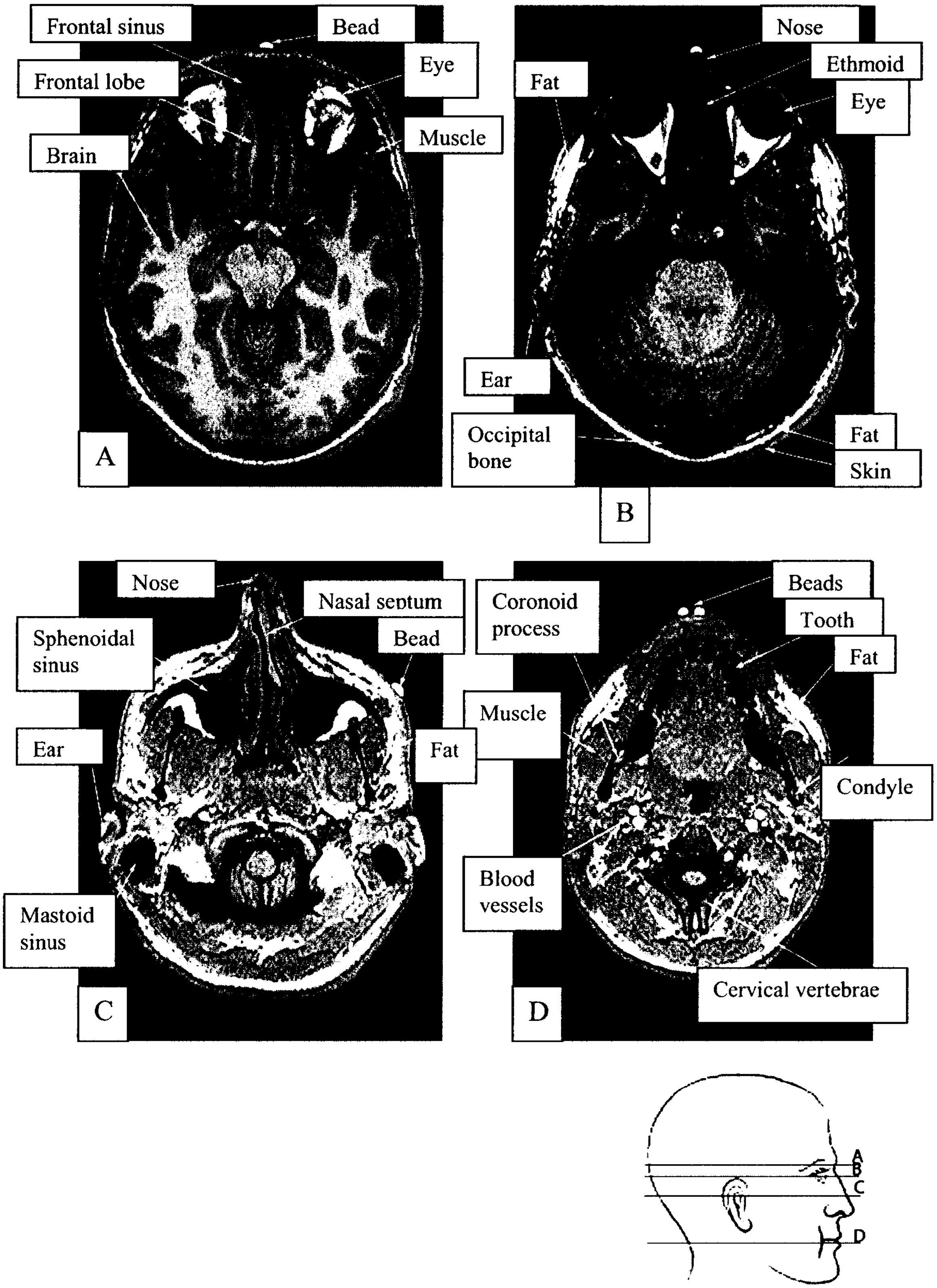
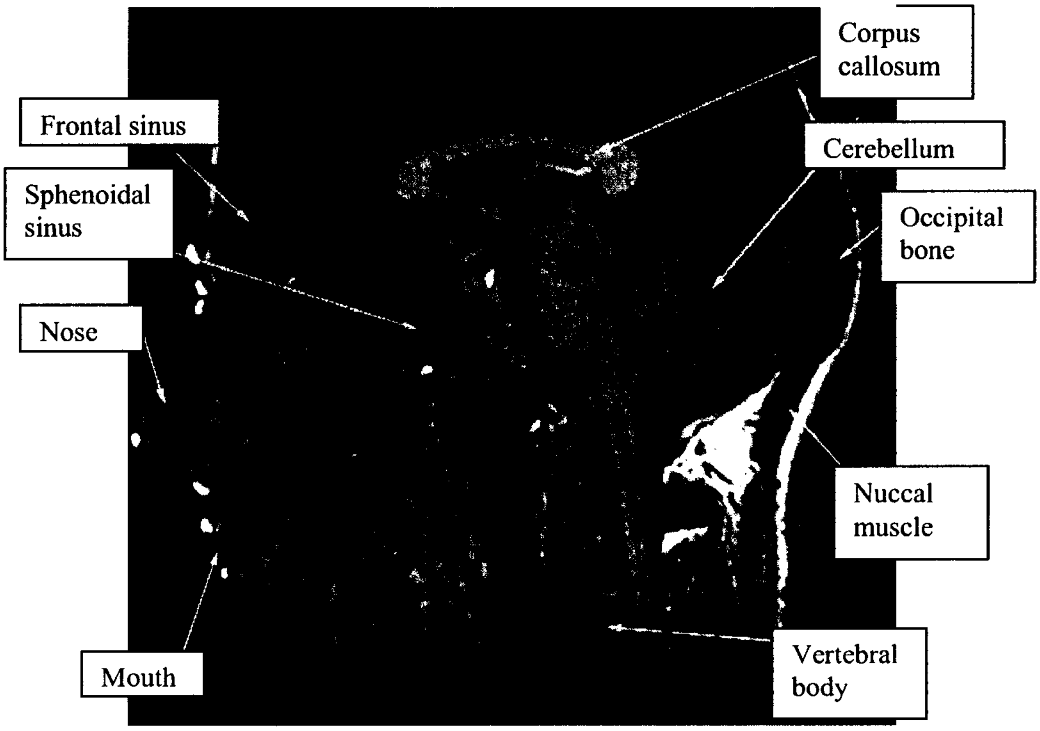


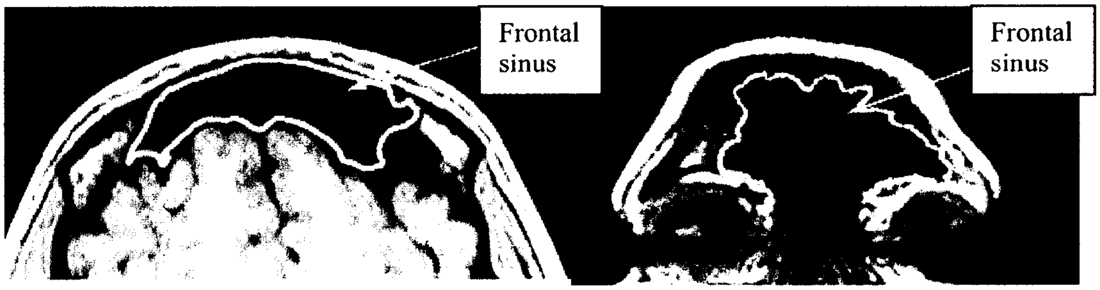
**Figure 10:** Illustration of a sagittal section through the head and neck




## The Frontal Sinuses

The frontal sinuses were one of the structures that were visible on the MR images. The sinuses appear as dark areas between the anterior portion of the forehead and the frontal lobes of the brain. These structures contain air and so are not dense (Figure 11), and the surrounding denser tissues provide definition of their outline.

**Figure 11:** Frontal sinus in axial and coronal planes outlined in light colour



The twins in this study have been qualitatively evaluated based on a series of verbal descriptors (Table 4). These qualitative descriptors are meant to augment the numerical evaluation of the frontal sinuses considered in the next section.

Table 5 illustrates the results of the qualitative descriptors. The sinuses are evaluated based on their overall shape in cross-section (axial plane), the visibility of the intersinus septum, presence of partial septa, whether the intersinus septum is centrally located, whether the left of right side is larger, if one of these sides persists superiorly over the other, and any other information considered important.

**Table 4:** Qualitative descriptors used in this research

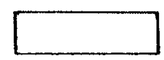
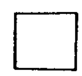
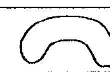
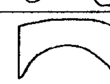
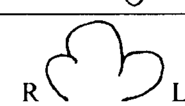
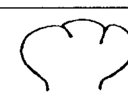
| Term | Description | Diagram |
|---|---|---|
| 'Rectangular' | Shape in the axial plane - at least twice as wide (laterally) than it is deep (anterior-posteriorly). |  |
| 'Square' | Shape (axial) more equal in width and depth |  |
| 'Irregular' | Shape (axial) not fit either rectangular or square, but indescribable shape | |
| 'Curved' | Shape (axial) Where the lateral elements become more posterior than the medial element |  |
| 'Deeper edges' | Shape (axial) Where the lateral elements are more deep laterally than medially |  |
| 'Thins' | To become more narrow, usually as moves superiorly. Thin to be narrow | |
| 'Slanted 45°' | Cross-sectional shape is angled 45° towards the posterior |  |
| 'Higher' | Coronal plane – to be superior. E.g. R side may exist superior to L. |   |
| 'Wider' | To have a larger transverse measurement. E.g. L is wider than R | |
| 'Over orbits' | The sinus exists directly above the orbits | |
| 'Scalloped' | Coronal plane – superior borders are semi-circular |  |

**Table 5**: Results of verbal descriptors of the frontal sinuses

| Twin | Overall shape (axial) | Intersinus septum | Partial Septa? | Central intersinus septum | Biggest side | One side persistent ? | Other |
|---|---|---|---|---|---|---|---|
| A1 | Irregular, lobes of brain intrude | Yes, visible | Possible 1 | Central | L | L over R | L sinus is bigger & slightly wider than R |
| A2 | Irregular, lobes of brain intrude, less than sister | Yes, off to R | 1, possibly 2 | Septum off to R | L is very large. R is small | L is higher and wider than R | L. sinus thins superiorly |
| B1 | Rectangular | Yes, visible | Yes, L side | Off to R side | L | L slightly superior side over R | L sinus in centre and side, R only side. |
| B2 | Rectangular | Off to R side | Yes, 1 | No, off to R | L, much bigger | L sinus higher and wider | L side is bigger and deeper than R. R is small |
| C1 | Small, barely rectangular | Yes, very nice | No | Yes | R, slightly | R for 4 slides | Almost square shape |
| C2 | Rectangular | Yes, barely visible | Possibly | Central | Equal | No | R slightly deeper, 2 R sinuses, 1 L |
| D1 | Small, rectangular, curved sides | Yes | No | Yes | L | Only L sinus, R very small | Nice L. Sinus not visible above eyes |
| D2 | Deeper at edges, | Yes, slightly | No | Yes | L | Very small R | Sinuses only |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | rectangular | visible anteriorly | | | | sinus | slightly above eyes |
| E1 | Rectangular, deep central fissure in brain | Yes, | No | Yes, L slightly bigger | L slightly bigger | L | Scalloped borders. Sinuses v. small. White matter, marrow ? |
| E2 | Thin & curved, almost square | Hard to see, but visible | 1 possibly others | Yes | Equal | No | 3 distinct scallops, small sinuses. Not above orbits. White matter |
| F1 | Irregular, deeper laterally | Yes on R | At least 3 | R | L much bigger than R | No | Very large sinus. Deepest medially scalloped borders |
| F2 | Irregular, R mostly rectangular, L slanted 45° | Yes, very nice | 2 partial | L | R side big, small L side. | No | 1 central sinus, then 1 either side. Prob. Largest R sinus. V. high |
| G1 | Rectangular, curved laterally | Yes, off centre to L | No | Yes | R bigger slightly | R for 2 slides | R side of head higher than L, head tilted |
| G2 | Deep brain fissure, | Yes | No | Yes | R bigger | R for 4 slides | V. small L |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | rectangular, slanted | | | | | | frontal sinus. R is wider and higher than L |
| H1 | V large, round & curved | Yes, slightly visible | At least 3 | Central | Equal | L slightly over R | Very nice sinus. 4 lobes. V large sinuses |
| H2 | Large & curved. Irregular | Start in centre then off to R. Visible | 2? | No off to L | L much larger than R | L over R | Thins as get superior. Over orbits. L is large, R sinus is small |
| I1 | Rectangular, deep brain fissure | Not visible | None visible | Yes | Equal | No | Curved, small sinuses. Bigger laterally |
| I2 | Deep at edges | Yes | Yes, 1 | Central | R slightly | R. Pocket of L in middle persists | R higher & wider. Sinuses wide |

## Qualitative Discussion

The qualitative descriptors of the twins provide basic information on the morphology of the frontal sinuses in the axial plane. The conclusions discussed are tentative as there are no guidelines in place for this form of evaluation. Twins were compared to each other looking for patterns of similarities and differences based on the verbal descriptors used above. Table 6 illustrates the results.

**Table 6** Comparison of similarities and differences in verbal descriptors categories

| Twin Set | Descriptors that are the same | Descriptors that are different |
|---|---|---|
| A | - Overall shape<br>- Persistent side<br>- Largest side | - Visibility of intersinus septum<br>- # of partial septa<br>- Intrusion of the frontal lobes |
| B | - Overall shape<br>- Intersinus septum<br>- # partial septa<br>- Largest side (L bigger than R) | |
| C | - Overall shape | - Visibility of intersinus septum<br>- Persistent side<br>- Largest side<br>- # of partial septa |
| D | - Overall shape<br>- Persistent side<br>- Largest side<br>- # of partial septa<br>- Centrality of intersinus septum | - Height of L sinus |
| E | - Visibility of intersinus septum<br>- Scalloped borders<br>- Small sinuses | - Overall shape<br>- # partial septa<br>- Persistent side<br>- Largest side |
| F | - Overall shape<br>- Persistent side<br>- Size of sinuses | - # partial septa<br>- Largest side |
| G | - Overall shape<br>- # partial septa<br>- Persistent side<br>- Largest side<br>- Visibility of intersinus septum | - Centrality of intersinus septum |
| H | - Overall shape<br>- Visibility of intersinus septum<br>- Persistent side | - # of partial septa<br>- Centrality of intersinus septum<br>- Largest side |
| I | - Overall shape | - Visibility of intersinus septum<br>- # of partial septa<br>- Size of sinuses<br>- Persistent side<br>- Largest side |

The twin sets that were the most similar, those having many more similarities than differences in the results of the verbal descriptors, are sets B, D and G. These three sets are all female. The twins with the most difference when examining the verbal descriptors are sets C and I, one set is female and the other male. Sets A, E, F and H have relatively equal numbers of similarities and difference in the verbal descriptors.

Overall shape was the descriptor most commonly similar among the twin sets. Only one set, E, had a difference between the twins in this category. The number of partial septa was the descriptor that was most commonly different between the twins. However, this category was often difficult to evaluate as the partial septa were hard to visualize on the images.

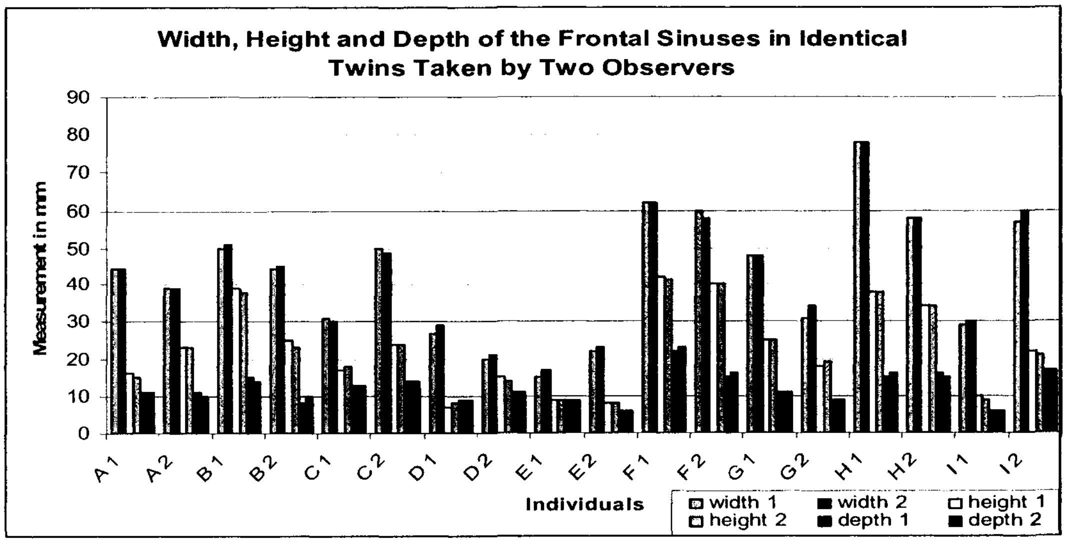
Most often the left sinus is the largest side. It is intriguing that the twins are not all the same in the size of the left and right sinuses or which one persists over the other. Some of the sets show similarities in the size of the left and right sinuses or have the same sinus persisting superiorly, while others show distinct differences. Nine individuals (50%) have the left sinus as larger than the right, four individuals (22%) have equal right and left sinuses and the remaining five individuals (28%) have larger right than left sinuses. Of these, four sets out of the nine sets total have the same sinus, either left or right, as larger. Of these four sets, three sets (75%) have the left larger than the right. It is possible that this is significant, but a larger sample size is required to test this observation.

The twins were also evaluated quantitatively. Measurements were taken of the maximum height, width and depth of the frontal sinuses. Height was usually taken on the sagittal or coronal planes, depth was taken in the axial plane and width was taken in the coronal plane. The right and left sinuses were treated as a whole structure, since in some individuals they were difficult to individualise. Two observers took measurements at separate times. One observer was an experienced radiologist; the other observer is the author. The measurements of the twins are illustrated in Table 7 and are also depicted graphically in Figure 12 for comparison.

**Table 7**: Measurements of the width, height and depth of the frontal sinuses

| **Name** | **W1** | **W2** | **Diff 1-2** | **H1** | **H2** | **Diff 1-2** | **D1** | **D2** | **Diff 1-2** |
|---|---|---|---|---|---|---|---|---|---|
| A1 ♀ | 44 | 44 | 0 | 16 | 15 | 1 | 11 | 11 | 0 |
| A2 ♀ | 39 | 39 | 0 | 23 | 23 | 0 | 11 | 10 | 1 |
| B1 ♀ | 50 | 51 | -1 | 39 | 38 | 1 | 15 | 14 | 1 |
| B2 ♀ | 44 | 45 | -1 | 25 | 23 | 2 | 8 | 10 | -2 |
| C1 ♀ | 31 | 30 | 1 | 17 | 18 | -1 | 13 | 13 | 0 |
| C2 ♀ | 50 | 49 | 1 | 24 | 24 | 0 | 14 | 14 | 0 |
| D1 ♀ | 27 | 29 | -2 | 7 | 8 | -1 | 9 | 9 | 0 |
| D2 ♀ | 20 | 21 | -1 | 15 | 14 | 1 | 11 | 11 | 0 |
| E1 ♀ | 15 | 17 | -2 | 9 | 9 | 0 | 9 | 9 | 0 |
| E2 ♀ | 22 | 23 | -1 | 8 | 8 | 0 | 6 | 6 | 0 |
| F1 ♀ | 62 | 62 | 0 | 42 | 41 | 1 | 22 | 23 | -1 |
| F2 ♀ | 60 | 58 | 2 | 40 | 40 | 0 | 15 | 16 | -1 |
| G1 ♀ | 48 | 48 | 0 | 25 | 25 | 0 | 11 | 11 | 0 |
| G2 ♀ | 31 | 34 | -3 | 18 | 19 | -1 | 9 | 9 | 0 |
| H1 ♂ | 78 | 78 | 0 | 38 | 38 | 0 | 15 | 16 | -1 |
| H2 ♂ | 58 | 58 | 0 | 34 | 34 | 0 | 16 | 15 | 1 |
| I1 ♂ | 29 | 30 | -1 | 10 | 9 | 1 | 6 | 6 | 0 |
| I2 ♂ | 57 | 60 | -3 | 22 | 21 | 1 | 17 | 17 | 0 |
| MEAN | 42.5 | 43.11 | -0.61 | 22.89 | 22.61 | 0.28 | 12.11 | 11.39 | -0.11 |
| ♀MEAN | **38.79** | **39.29** | | **22.00** | **21.79** | | **11.71** | **11.85** | |
| ♂MEAN | **55.50** | **56.50** | | **26.00** | **25.50** | | **13.50** | **13.50** | |
| ST DEV | 16.54 | 16.07 | 1.33 | 11.26 | 11.1 | 0.83 | 4.03 | 6.05 | 0.76 |

**Figure 12:** Width, height and depth of the frontal sinuses

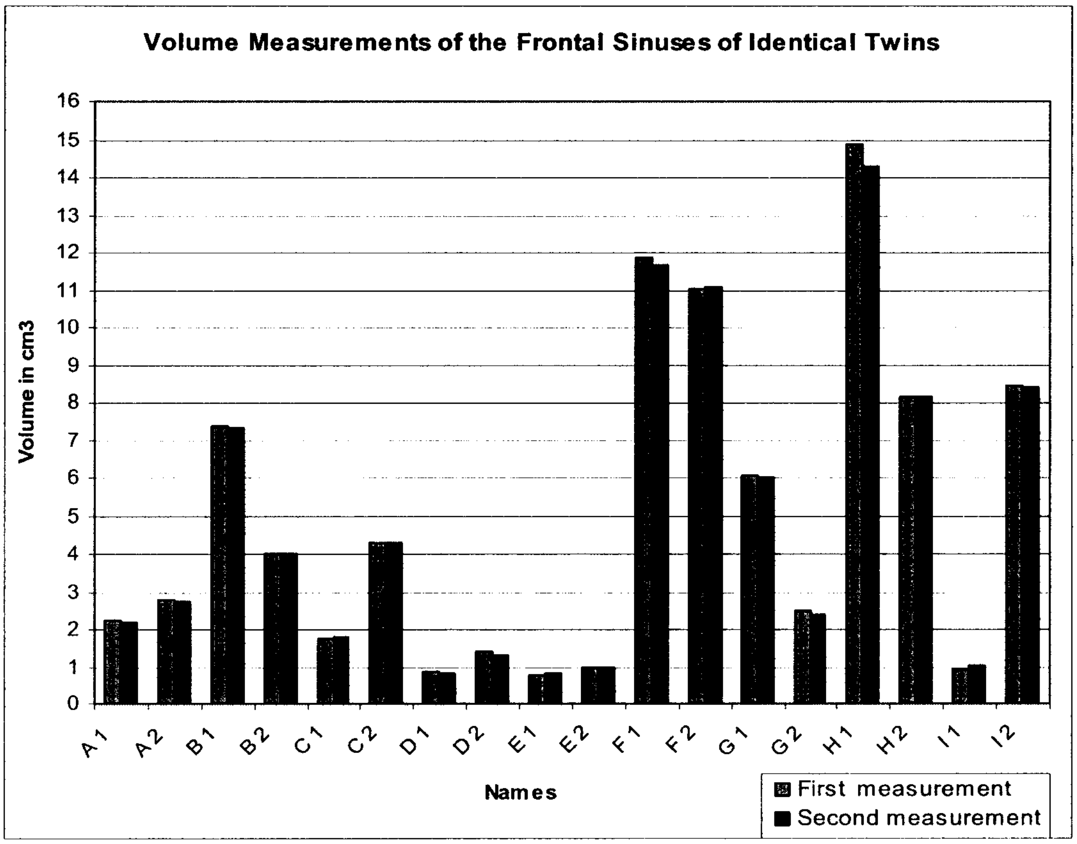


Volume measurements were also taken of the frontal sinuses of the participants. Table 8 illustrates the two sets of measurements taken of the volume of the frontal sinuses and Figure 13 outlines the volume graphically.

**Table 8**: Measurements of the volume of the frontal sinuses of identical twins

| **Name** | **First Volume measurement ($cm^3$)** | **Second volume measurement ($cm^3$)** | **Difference between measurement 1 and 2** |
|---|---|---|---|
| A1 ♀ | 2.220 | 2.215 | 0.005 |
| A2 ♀ | 2.775 | 2.742 | 0.033 |
| B1 ♀ | 7.364 | 7.322 | 0.042 |
| B2 ♀ | 3.988 | 4.017 | -0.029 |
| C1 ♀ | 1.789 | 1.822 | -0.033 |
| C2 ♀ | 4.283 | 4.275 | 0.008 |
| D1 ♀ | 0.869 | 0.818 | 0.051 |
| D2 ♀ | 1.398 | 1.303 | 0.095 |
| E1 ♀ | 0.789 | 0.840 | -0.051 |
| E2 ♀ | 0.983 | 0.959 | 0.024 |
| F1 ♀ | 11.855 | 11.654 | 0.201 |
| F2 ♀ | 11.022 | 11.085 | -0.063 |
| G1 ♀ | 6.070 | 5.990 | 0.080 |
| G2 ♀ | 2.471 | 2.392 | 0.079 |
| H1 ♂ | 14.883 | 14.270 | 0.613 |
| H2 ♂ | 8.125 | 8.147 | -0.022 |
| I1 ♂ | 0.925 | 1.030 | -0.105 |
| I2 ♂ | 8.444 | 8.367 | 0.077 |
| MEAN | 5.012 | 4.958 | 0.056 |
| **♀ MEAN** | **4.131** | **4.102** | **0.032** |
| **♂ MEAN** | **8.094** | **7.954** | **0.141** |
| ST. DEV | 4.344 | 4.247 | 0.160 |

**Figure 13:** Graph of the volume of the frontal sinuses




## Quantitative Data Analysis

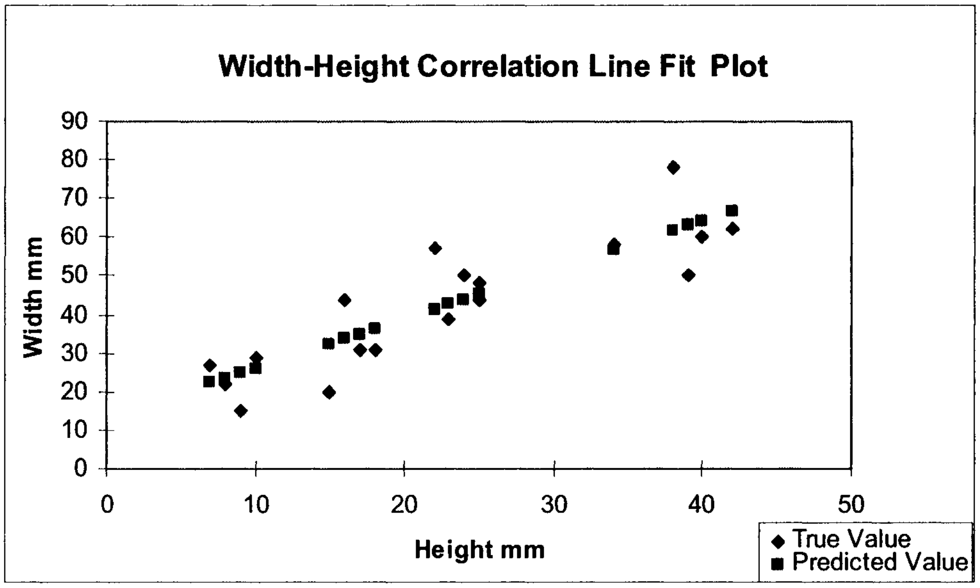
Once the height, width and depth measurements of the frontal sinuses were obtained it was then necessary to see if there exists a statistical difference between the sets of measurements. To do this a paired T-test was constructed. This test is used when observations are collected in pairs such as when two observers collect data, or one observer collects data twice. The null hypothesis was that there was no statistical difference between the observers' measurements, while the alternative hypothesis was that a statistical difference exists. The results of the paired T-test for height = 1.43, width = -1.94, depth = -0.062 and volume = 1.433. For 17 degrees of freedom and for a 95%

confidence interval the t value is 2.11. Since the values for width, height, depth and volume are all below the critical value this illustrates that there is no statistical difference between observers' measurements.

Next, the twins were tested to see if there were differences between them. This was done using the Chi square statistic, which provides information on the variance of a sample. The results of the chi square statistic for Observer One are height = 8.34, width = 9.00, depth = 9.00 and volume = 7.50. For Observer Two the results of the Chi square are: height = 7.20, width = 8.98, depth = 9.00 and volume = 7.99. For the test to be significant at the 95% confidence interval for a two-tailed test the results would have to be greater than 15.507 or less than 2.032. Since the results obtained for the chi squared test in on this sample are within the values it cannot be proven that there is significant variance between the twins in this sample. This is a very small sample and looking at difference between the twins makes the sample size smaller by half. When the sample size is small it is difficult to accept the assumption that it is of normal distribution. Therefore, the Chi square test performed on this sample and the results of it are only a guideline to what is going on in the sample. If we look at the absolute scores for the twins in this research it is obvious that there are some large differences between the values of some twins, while for other twins' the values are similar. It is also obvious when looking at the absolute measurement scores that there is less difference between the scores of depth and the scores of width or height. These would be interesting points to explore given a larger sample size.

To test the correlation between the variables of measurement (height, width and depth) regression analysis can be performed. Regression analysis is used to illustrate the correlation between different values. In this case regression was done between the two values of: width-height, width-depth and height-depth. It was found that the $r^2$ values are as follows for observer one's measurement: width-height = 0.868 (Figure 14), width-depth = 0.746 (Figure 15) and height-depth = 0.793 (Figure 16). For observer two the $r^2$ values were as follows: width-height = 0.853, width-depth = 0.772, and height-depth = 0.809. An $r^2$ value of 0 indicates no relationship, whereas a value of 1 indicates a perfect relationship between two variables. In the case of this research all the relationships are positive and can be considered to be moderately to well correlated. The $r^2$ values are all significant to the 0.01 level (2-tailed). $R^2$ statistics were also performed to check for correlations between volume and the measurements of height, width and depth. The $r^2$ values for observer one's measurements are: volume-height =0.897 (Figure 17), volume-width = 0.933 (Figure 18), volume-depth = 0.788 (Figure 19). For observer two's measurements the $r^2$ values are as follows: volume-height =0.903, volume-width = 0.935, volume-depth = 0.830. All of these values are significant at the 0.01 level (2-tailed). These groupings show quite high correlations, especially the relationship between volume and width and height for observer two.

**Figure 14**: Width-Height Correlation Plot (Observer one) $r^2 = 0.868$




"Predicted value" is the direct correlation between the two variables

**Figure 15**: Width-Depth Correlation Plot (Observer one) $r^2 = 0.746$

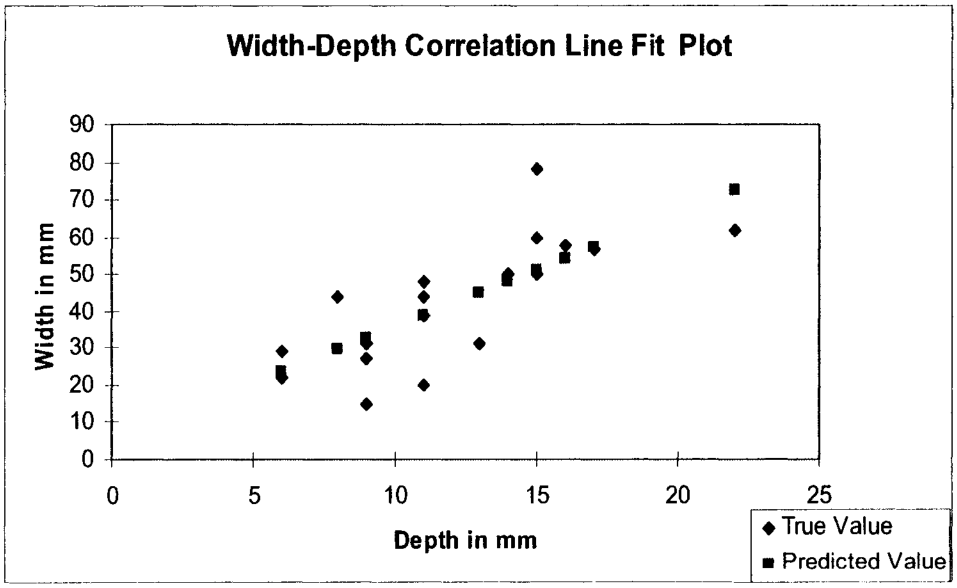


**Figure 16**: Height-Depth Correlation Plot (Observer one) $r^2 = 0.793$

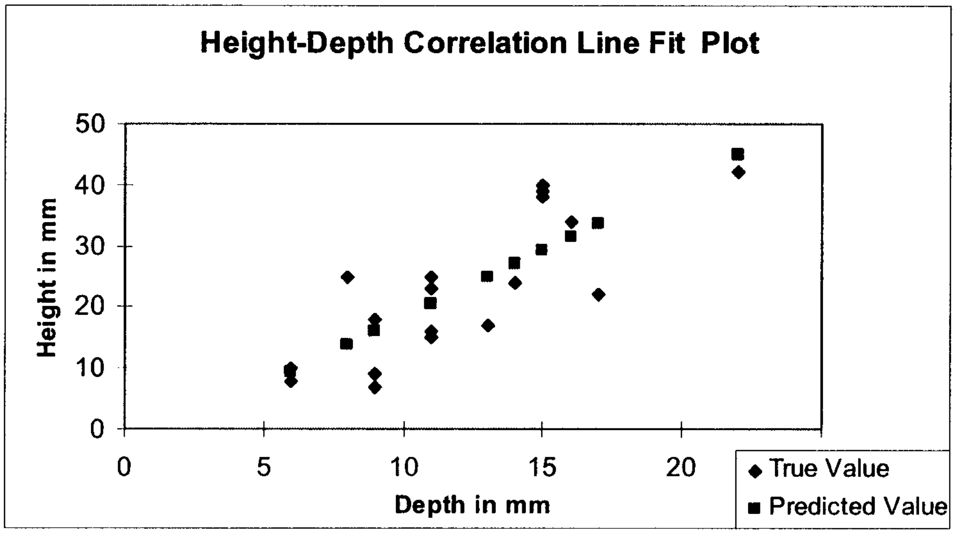



**Figure 17**: Height-Volume Correlation Plot (Observer one) $r^2 = 0.897$

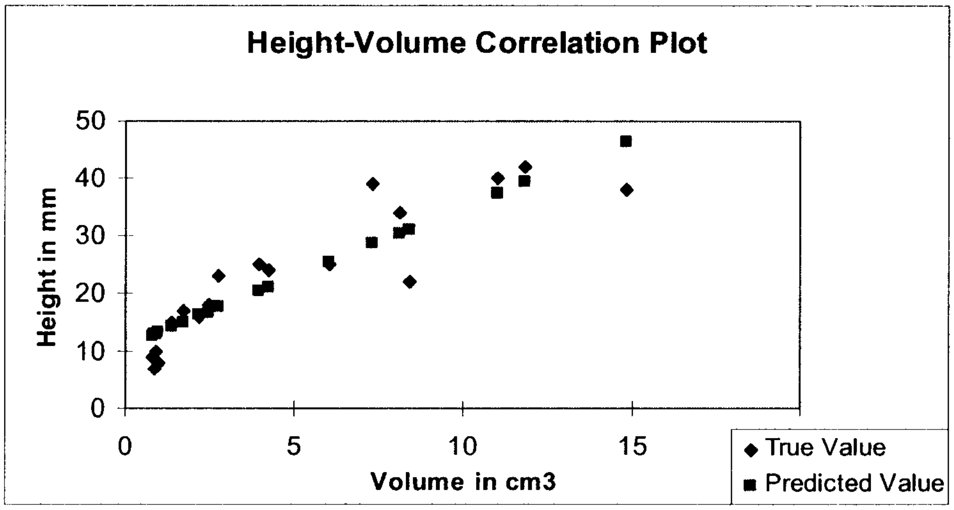


**Figure 18**: Width-Volume Correlation Plot (Observer one) $r^2 = 0.933$

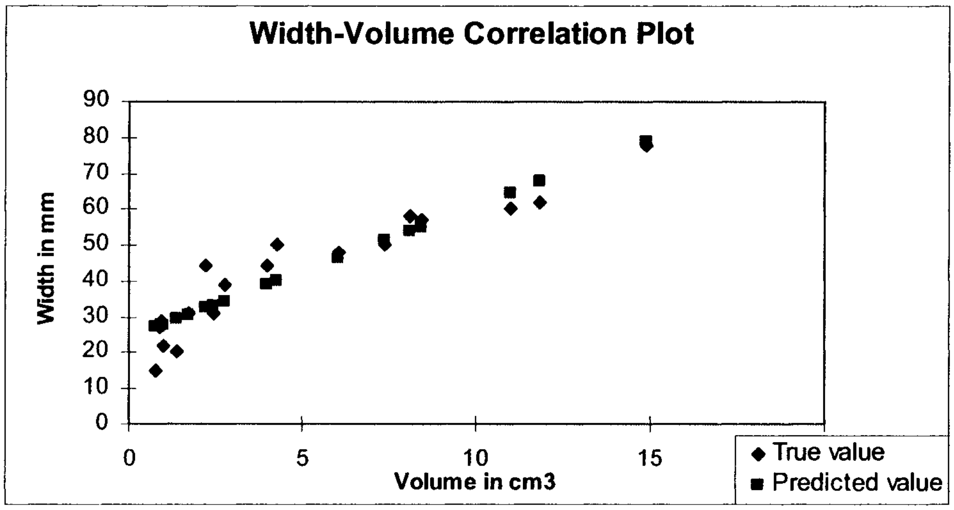
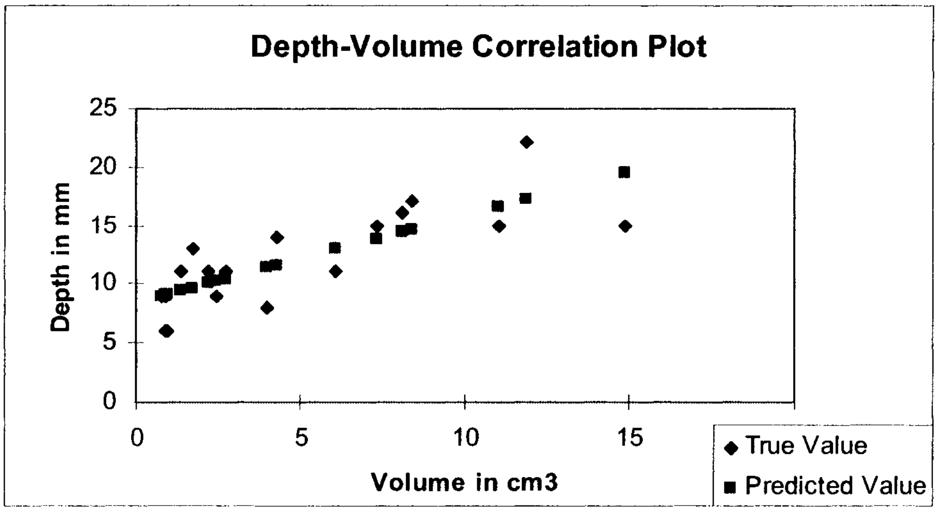
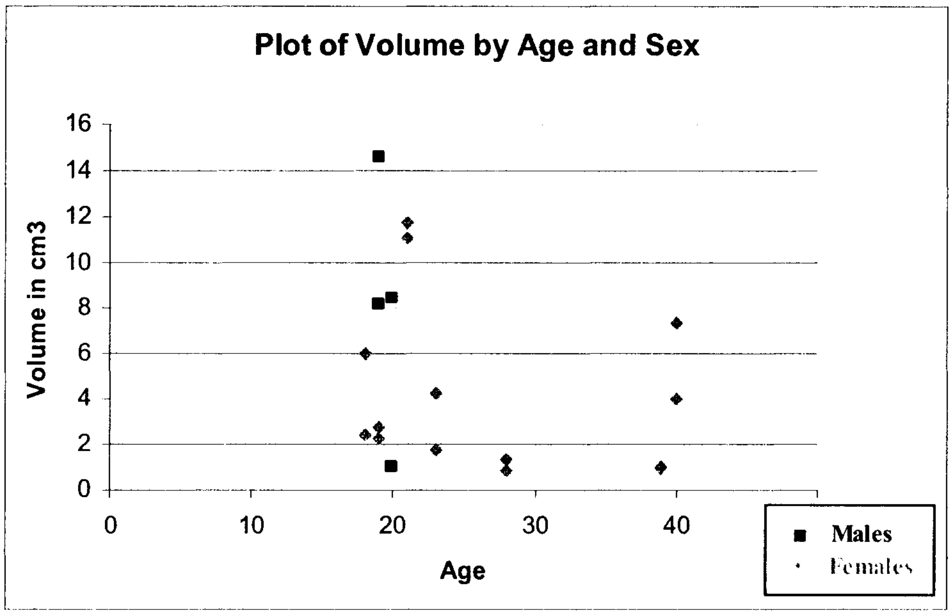



**Figure 19**: Depth-Volume Correlation Plot (Observer one) $r^2 = 0.788$




A plot was also made to see if there was a relationship between the volume of the frontal sinuses and the age of the participants involved in this study. Sperber (2001) has commented that all the paranasal sinuses appear to increase in size with age as with advancing age the walls of the frontal sinuses become thinner and therefore the sinuses appear larger (Krogman, 1962). Figure 20 illustrates a cross-sectional sample, with males and females marked separately. The results would almost certainly be more conclusive if this was a longitudinal study, and therefore able to evaluate if volume increased with age. From the chart it is can be seen that there is no real increase in volume of the frontal sinuses with age for adults, and the scatterplot appears to be of a completely random distribution. However, the sample size used in this study is small and there are not an equal number of males and females, especially in the upper age category. To study if the volume increased with age in a cross-sectional sample such as this one, participants from all ages would be required; this would also make the sample size larger.

**Figure 20:** Plot of Volume by Age and Sex




Lastly, in referring to Tables 7 and 8 a basic analysis of the sexes can be performed on this small sample. Several authors (Krogman, 1962; Buckland-Wright, 1970; Szilvassy, 1981; Brown, 1984; Harris et al., 1987b; Lynnerup and Homoe, 1999; Prossinger, 2001) have reported that males have larger frontal sinuses than females. Comparing the female and male averages to the overall average of the sample in all but one case the female average is smaller than the overall average. The only case where it is larger is in the depth measurements of Observer Two. In this case the female average exceeds the overall average by only 0.46 $cm^3$. In this sample the largest frontal sinuses belonged to Twin H1, a male, with a volume average of 14.577 $cm^3$, the next largest sinuses belonged to a female set who were very close to each other in their volume measurements, F1 being 11.755 $cm^3$ and F2 being 11.054 $cm^3$. The next largest frontal sinuses belonged to a male, Twin I2, and measured on average 8.406 $cm^3$, after that Twin G1 a female, possessed a sinus that measured 6.030 $cm^3$. There was one male frontal sinus that was extremely small at 0.978 $cm^3$, a measurement more typical of the females in the group. Overall the results from this research sample are consistent with other researchers' findings that male frontal sinuses seem to be larger than those of females.

## Quantitative Discussion

Due to the vast amount of data that has been collected on the measurements of the frontal sinuses, comparison of these data to that collected previously is possible. Table 9 compares the results of previous results to the current investigation for height, width and depth of the frontal sinuses.

**Table 9**: Measurements of the Height, Width and Depth of the Frontal Sinuses, comparing other results with this study

| Researcher(s) | Height (in mm) | Width (in mm) | Depth (in mm) |
|---|---|---|---|
| Turner (1901) | | | 2-16 |
| Jackson and Coates (1929) | 28 | 24 | 20 |
| Hanjis & Pozdenova (1972) | 27 | 24.35 | 10.65 |
| Ritter (1973) | 28 | 27 | 17 |
| Pedro (1978) | 6-45 | | |
| Weiglein (1999) | 24 | 29 | 20 |
| Nambiar et al. (1999) | 24.3 (5-66) | | |
| Kirk et al. (2002) | 41.8 (24-67) | 71.29 (36-141) | |
| Anon et al (1996) | 30 | 25 | 19 |
| **This study** | **22.8** | **42.8** | **11.8** |

From Table 9 it is obvious that there is great variation in the height, width and depth of the frontal sinuses. The results of this study are consistent for height and depth variables. While the result for width is within the range that other authors have found, most researchers are reporting an average between 24 and 29 mm. The result of 42.8 mm from this study is approximately twice the modal average, although it is much less than the highest average of 71.29 mm reported by Kirk et al. (2002).

The average measurement of volume in this study is $4.99cm^3$ ($0.79$-$14.88cm^3$) and is slightly lower than the average results reported by other researchers; seen in Table 10. However, this average is close to the average volume reported by Hajnis and Pozdenova (1972) for one of their data subsets. It can be seen that the average mean of females ($4.1cm^3$) is smaller than the mean volume of the males ($8.0cm^3$) in this study. These results are consistent with several authors (Turner, 1901; Buckland-Wright, 1970; Blaney, 1986; Harris et al., 1987b; Yoshino et al., 1987; Lynnerup et al., 1999;

Prossinger, 2001) who have commented that male frontal sinuses tend to be larger than those of females. It should be remembered that the size of the sample under analysis in this research study is small (n = 18) and that there are only four males in the group.

**Table 10**: Volume measurements comparing other results with this study

| Researcher(s) | Volume (in $cm^3$) |
|---|---|
| Braune and Clausen (1877)* | 6.1 |
| Schaeffer, (1920) | 1-45 |
| Jackson and Coates (1929) | 14 (1-45) |
| Bezold (1943)* | 10.5 |
| Schumacher (1972)* | 7.7 |
| Hajnis and Pozdenova (1972) | 8 (6.2, 9, 4.83 and 13.75†) |
| Koppe and Schumacher (1999)* | 6.83 |
| Anon et al. (1996) | 10.02 (0-37) |
| **This study** | **4.99 (0.79-14.88)** |

*Cited in Spoor and Konneveld, 1999. †Averages of four typological groups

While there does not exist significant differences between the two observers in this study for height, width and depth and the first and second measurements for volume, there are some absolute differences. There are several plausible reasons for these differences. In the height, width and depth data, measurements were rounded by the radiologist (first observer) and this was repeated by the author (second observer). Small errors have been attributed to these rounding inconsistencies. Additionally, the ruler used to gather this data was extremely sensitive. Slight movements of the hand sometimes produced differences to the effect of 1 mm. To ensure the highest accuracy it was therefore critical to verify exactly the points of contact for the ruler. Differences in volume are likely attributable to different inclusions of bone cortex and intersinus septum as well as to which slides outlines were drawn on. In some cases the frontal sinus was extensively continuous with the ethmoidal sinus. In these individuals it was difficult to judge where the frontal sinus truly started and therefore, one measurement of the volume may include one more slide than the second measurement, or vice versa.

The shape of the frontal sinuses in this sample shows great variability but is consistent with other authors' descriptions of these structures being "roughly pyramidal" (Jackson and Coates, 1929:22). This study illustrated that the sinuses frequently trespass on each other and that the intersinus septum is often not in the midline. There are often partial septa present which divide the sinus cavities. All researchers investigating the frontal sinuses have reported on great dissimilarity even within relatively small samples. For instance, Hajnis and Pozdenova (1972), who used 60 specimens from an archaeological collection from Bohemia, commented that their sample was very variable. The current sample is consistent with the findings of other researchers in its variability, with some individuals having large sinuses, while others are barely discernible. However, this sample does not contain any individuals who present frontal sinus agenesis. The amount of agenesis present in a population is also very variable between groups. Moreover, the lack of agenesis in this sample could be explained by the different methodology employed in this study. The traditional method for the assessment of frontal sinus morphology on x-rays employs a line being drawn to connect the superior edge of the orbits; this line delineates the base of the frontal sinuses. The reason for this procedure relates to the superimposition of the many tiny structures around the bridge of the nose. The frontal sinuses may indeed exist, but just not be present above this line, resulting in a "false positive" agenesis. MRI does not superimpose structures and therefore the baseline method is not necessary and smaller frontal sinuses are recognisable. In fact, in the sample there were some individuals who had very small sinuses, which did not grow above the level of the top of the orbits. These cases would represent agenesis if analysed using the baseline method on traditional radiographs.

## Conclusion

This chapter has looked at the results of the current study. This study was initiated for two reasons: to test the use of MR images to the research conducted by anthropologists and to look at the similarities and differences between the frontal sinuses of identical twins as represented on magnetic resonance images. This chapter details the many structures seen on MR scans that could potentially be of interest to physical anthropologists in the head and neck and establishes the usefulness of this technology to anthropological research. In addition to proving the value of MR to anthropology, this chapter provides information about the frontal sinuses of nine sets of identical twins. The frontal sinuses of these participants were analysed both qualitatively, using verbal descriptors, and quantitatively, using descriptive and inferential statistics for the measurements of height, width, depth and volume. This research found that the methodology used is highly repeatable, with no statistical difference existing between measurements taken by different researchers or by the same researcher on separate occasions. This chapter also illustrated the differences and similarities existing between genetically identical individuals. The quantitative discussion section explores the similarities and differences between the results of the current study and the previous work conducted by other researchers.

# Chapter Six - Conclusion

## Introduction

This study was undertaken to explore two fundamental questions: (1) generally - is magnetic resonance imaging technology useful to anthropological research and (2) specifically – how similar are the frontal sinuses of identical twins? MRI scans, along with computerized tomography, is increasingly being employed as the imaging technique of choice especially with respect to the head and neck regions in clinical and general medical practice. Physical anthropologists, particularly those that specialize in forensic anthropology, have a responsibility to keep up with current research trends and explore new avenues of image acquisition. Since MR images are being increasingly used to diagnose diseases and analyse the head and neck, this image format increasingly comprises more of the antemortem record generated by medical professionals. In the case of an unidentified decedent, medical records of suspected persons are often used in combination with other techniques to establish identity. One of the many areas of the body that is often used in such cases is the region of the frontal sinuses. Traditionally, medical examiners and anthropologists have made use of plane film x-ray images to make comparisons. But now, with a greater likelihood that antemortem images are in MR or CT format, anthropologists need to be flexible and experienced in the use of different imaging modalities. Therefore, this research study was partially undertaken to demonstrate the effectiveness of using the anatomical regions visible and definable on MR images.

The second aspect of this research was borne out by the sample itself – a small group of identical twins. The frontal sinuses have been used for almost 100 years as a point of individuality. There is little research conducted on the potential differences and similarities between identical twins. These twins possess exactly the same genetic material so any differences in the frontal sinuses should be a response to environmental factors, including nutrition, trauma or disease. Differences in the morphology of the frontal sinuses between genetically identical individuals would ultimately prove the usefulness of this structure in the quest to establish personal identity in a forensics context. With data on the measurements for height, width, depth and volume of the frontal sinuses from this small sample it was also possible to comment on correlations and inter- and intra-observer differences.

## Specific Conclusions

This work has established that MR images are useful for anthropological research questions involving evaluation of anatomical variability. MRI scans depict a multitude of structures that could and would be of interest to the physical anthropologist. Elements of the head and neck observed in the images generated by this study range from the nuchal muscles of the neck and vertebrae to the masseter and temporalis muscles, which contribute to chewing. The teeth, including the roots, are discernable, as are the maxillae and mandible, especially the condyles. Tissues of the nose, including the septum and nasal bones are visible. Areas of the brain, particularly the cerebellum, brain stem and lobes, appear clearly on MR images. The frontal sinuses and other paranasal sinuses (ethmoidal, sphenoidal and maxillary) can also be seen on the scans. An anthropologist needing to examine essentially any structure in the head, especially those with high water content, would benefit from the use of MR imaging.

Additionally, this investigation illustrated that three-dimensional information about the frontal sinuses (measurements of height, width, depth and volume) can be acquired from MR images. The fact that magnetic resonance imaging is conducted in three dimensions initially means that the resulting data can easily provide information about any structures in three dimensions. This makes it a superior technology to plane film x-ray imaging. The scans can be viewed in several planes (coronal, sagittal, axial) to provide detailed information on all aspects required for thorough research.

Acquiring three-dimensional images is both quick and painless for volunteers. The participants in this study were only required by the research team to be present for one hour in the facility and the two scans took approximately twelve minutes to carry out. Additional time was spent briefing participants, allowing them to ask questions, filling out safety forms and applying the gadolinium-agarose beads. Moreover, MR is considered a very safe way of obtaining images, while CT and x-ray both work by irradiating the subject. Radiation is known to be harmful and can cause cancers and other diseases. Magnetic resonance differs by measuring the resonance of hydrogen atoms in different structures in a magnetic field. There are no known side effects of being scanned by a magnetic resonance technology.

In regard to the frontal sinuses themselves, this study found that it was possible to evaluate the morphology of this structure both qualitatively and quantitatively. The qualitative results illustrate some interesting trends, particularly with regards to the verbal descriptors of overall shape and persistent side when examined in the axial plane. A larger sample size is required however, to test these preliminary findings, Specifically, it was found that the frontal sinuses could be measured. In this study the measurements were collected for maximum height, width, depth and volume. These measurements were then compared for the identical twins in the research sample. It was found that there were no statistically significant differences between the twins. Height, width, depth and volume measurements were also compared and there were moderate to high correlations found between these variables for the frontal sinuses, which would be expected. This shows that the frontal sinuses can be measured on MR images and qualitative and quantitative data gathered.

By simple observation of the absolute data of the measurements it can be seen that some of the twins are similar and others are not. The twins from set I for example are dissimilar in all measurement variables, whereas set F are similar especially in measurements of volume, height and width. These results illustrate that the morphology of the frontal sinus is determined not only by genetics, but also by environmental factors to some degree. The small sample size employed in this study prevents significant statistical conclusions from being drawn and the statistical analysis that has been conducted is only meant as a guideline and a precedent for further research. However, the diversity seen in twin groupings proves that the frontal sinus can be used as a personal identifier even in instances where the decedent has an identical twin.

By plotting the volume by age of the participants involved in this study some comments can be made about whether the frontal sinuses appear to increase with age. Krogman (1962) and Sperber (2001) have both observed that the frontal sinuses increase with age as a result of the breakdown of the bone from the inner table. Figure 20 in the Results and Discussion Chapter illustrates a random scatterplot of volume plotted by age.

These data do not agree with the other authors' findings, possibly suggesting that the volume does not increase in old age; however, this small cross-sectional sample cannot conclusively disprove these authors' assertions. A longitudinal study representing both sexes at every age would be able to provide a more decisive answer to the question of whether volume of the frontal sinuses increases with age.

Lastly, it was also possible with this sample to conclude something about the repeatability of the experiment by analysing inter- and intra-observer differences. The data on height, width and depth was collected by two different observers, one a trained radiologist with several years of experience, the other the author, an anthropology graduate student. Comparisons of the different sets of measurements with the use of a paired T-test illustrate that there is no statistically significant differences between these observers' measurements. The results of volume data was collected by the latter observer, but collected twice to test for intra-observer differences. Once more it was possible to conclude that there exists no statistically significant difference between the two sets of volume measurements. This information illustrates the reliability of the measurement methodology employed in this research and suggests that in a practical forensics situation high levels of continuity would be seen.

## Areas of further/future research

In general this research could be widened by increasing the sample size. A sample of eighteen individuals (nine sets of twins) is considered a small clinical sample, and this diminutive number creates many problems. Small samples are notoriously difficult to conduct statistical analysis on as they do not typically represent the variety in data required to make solid assumptions. Therefore, any statistical analysis that is conducted on a small sample provides only suggestions as to what is going on in the larger population. In addition, it would be interesting, especially from an anthropological standpoint, to widen the ethnicities included in the sample. The current research sample only includes those of Caucasian ancestry. Other researchers (Harris et al., 1987a & b) have conducted research based on the racial differences of the frontal sinuses and it would be interesting to see if there were the same correlations existing and to the same degree as in the sample from this study. The sample is also constricted to individuals between 18 and 39 years. It would be beneficial to broaden the sample to include both younger and older individuals, especially in the older category since there is some suggestion by other researchers that the frontal sinuses actually increase with advancing age as the bone around them starts to thin. Ideally, conclusions based on a longitudinal study would be preferable; however, the inherent problems in such samples (such as the many years it takes to come up with any conclusions) usually means that cross-sectional samples are preferred. In addition to being able to use more sophisticated statistical analyses and with more certainty, a larger sample would also furnish statistical analysis of subsets of the population for comparison (for example, males to females, or younger individuals to older ones).

Additional future research could explore familial traits and features. Information gathered on monozygotic twins, triplets or immediate relatives (such as parents or children) could help us understand more about the development and perhaps function of the frontal sinuses in humans. These data could provide information on the amount of input genetic and environmental factors have on the morphology of the frontal sinuses, or potentially provide a "family pattern" to the frontal sinuses.

It would be interesting to expand the research focus to include the other paranasal sinuses to see if there is a correlation between the size and shape of the frontal sinuses and the size and shape of the maxillary, ethmoidal and sphenoidal sinuses. These data could assist in establishing the role of these sinuses for human beings or possibly the relationship of these sinuses to each other. To date, the author is unaware of any research that has been conducted to investigate a correlation of such nature.

Some researchers, particularly in earlier works (Brothwell et al., 1968; Schuller, 1943; Marciniak & Nizankowski, 1959), have commented on a possible connection between a persistent metopic suture and frontal sinus agenesis. In this study, using MR technology, it was not possible to detect the presence or absence of metopic sutures. It would be possible to explore this potential relationship in further research, perhaps through the comparison of MR images to computerized tomography and x-ray images. This approach would provide a more complete picture of the frontal sinuses and lead to comparisons between the imaging modalities. For instance, such a study could aid in transferring terminology used on x-ray images to MRI and CT images. Authors such as Yoshino et al.,(1987) and Reichs and Dorian, (1992) have constructed systems of analysis that rely on coding certain elements that can show up as part of the frontal sinus architecture to conclude if two images are of the same person. To be able to fully incorporate these structures into the analysis of the frontal sinuses would be a benefit to creating universal standards for the analysis of frontal sinus morphology.

The twins used in this study are monozygotic and therefore genetically identical. The differences seen in the frontal sinuses of these related individuals must therefore be the result of some combination of environmental factors. From research we know that the morphology of the frontal sinuses is altered by environmental factors such as trauma and disease. A further point of exploration would consider the medical history of participants in an attempt to link specific events to the formation and differences seen in genetically identical persons.

## Conclusion

This thesis research was conducted to attempt to answer two primary research questions regarding the use of MR imaging data to anthropological interests and the similarities and differences in the morphology (size and shape) of the frontal sinuses of a small sample of identical twins. There were eighteen individuals, or nine sets of identical twins used in this study. The twins ranged in age from 18 years to 39 years, with a mean age of 25.2 years; seven sets were female twins and two sets were male twins. The participants had MRIs conducted at the University of Alberta Research MRI Facility in the summer of 2004. The subjects were evaluated qualitatively using verbal descriptors and the results of this examination found some tentative trends in the sample. Measurements of height, width and depth of the frontal sinuses were taken by two different observers with differing degrees of experience. The volume was taken by the author on each individual twice. These data were analysed and it was found that there were some differences between the twins, some twins being more similar to each other than other sets. It was also seen that there exists a moderate to high correlation between the measurements of height, width, depth and volume for the frontal sinuses of the participants. No statistically significant differences were seen between the inter- and intra-observer measurements. This research study is ultimately able to conclude that magnetic resonance imaging is of use to research questions asked in the field of physical anthropology. In addition it is able to say that there exists some difference between the frontal sinuses of identical twins proving the value of this structure, and the future use of MRI, to forensic anthropological work on personal identity.

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# Appendix One – Forensic Anthropology Case Studies

This section details the case studies where the frontal sinus has been used to resolve personal identity. There are numerous examples in the literature where the pattern or morphology of the frontal sinuses have been used since their first recorded use by Culbert and Law in 1927. The majority of these cases represent instances of where antemortem and postmortem images of the frontal sinuses have been compared using traditional radiographs; however, more recent case studies have been published that compare images using computerised tomography (CT) generated data.

1. Stewart (1979) used the morphology of the frontal sinus on the completely defleshed and scattered remains of a black, adult male. The remains were found with a broken hospital identification bracelet. This provided investigators with a suspected identification for the remains. Investigators were able to find a cranial x-ray showing a very large frontal sinus and a distinct pattern of compartmentalization. This was compared with a postmortem x-ray taken of the unidentified remains. The x-rays matched and the identity was resolved (Stewart, 1979:251).

2. A human skull was washed up in Boston Harbour on July 6, 1977 (Atkins and Potsaid, 1978). One month later skeletal remains consisting of a torso and limbs with some fleshy parts were recovered near where the skull was found. In the absence of the mandible and all but one maxillary molar as well as the means to conduct fingerprint identification, another method to confirm identity was needed. The remains were thought to originate from a boat that overturned in the harbour. Radiographs of the suspected victim were obtained showing fracture of right 5$^{th}$ metacarpal bone and an earlier fracture through the right hand, as well as skull x-rays. Atkins and Potsaid's (1978) comparison

of antemortem and postmortem skull radiographs show, through observation and superimposition, that the form of the frontal and other paranasal sinuses, as well as the mastoid air cells, were identical. In addition, there was a match to the fractures on the right hand (Atkins and Potsaid, 1978:2308).

3. In March 1980, skeletonized human remains were found (Murphy and Gantner, 1982). A television announcement led to a suspected identity. Dental and prosthodontic evidence was recovered, but unfortunately all records for the suspected decedent had been previously destroyed. Postmortem radiographs of the deceased showed excellent mineralization with closed epiphyses and no evidence of trauma or disease, indicating that the individual was between 18 and 25 years of age (later established at 22 years). Antemortem radiographs were located of a skull from the suspected individual and it was determined that the frontal sinus pattern among other structures was identical (Murphy and Gantner, 1982:12).

4. Ubelaker (1984) was involved in a case in 1980 where he was brought a well-preserved human calvarium with soft-tissue present. The calvarium showed no sign of injury, but was missing the facial bones and the cranial base. The remains were suspected to be that of a known female prostitute who was thought to have been murdered. Positive identification was not possible from the remains alone, and although a photograph was obtained of the suspected victim, this did not aid in resolving identity because of the missing facial bones. Lateral and frontal radiographs were found of the suspected victim that had been taken shortly before her death. Postmortem radiographs were then taken from the same angles. Comparisons of the lateral radiographs showed identical features in the lower frontal region, especially in the size and shape of the sella

turcica. When comparing the frontal views, Ubelaker saw an exact match in the orbital region and size and pattern of the frontal sinus (Ubelaker, 1984:400). Ubelaker provided court testimony to this effect.

5. Yoshino et al. (1987) worked on a case where the body was found in a forest. The presumed identity was a 59-year-old male, who had been reported missing four years prior. A postmortem radiograph was taken a similar angle to the recovered antemortem image. The two images were coded according to Yoshino et al's classification system for categories of the frontal sinus (area size, bilateral asymmetry, superiority of side, outline of the upper border - left and right side, the partial septa, and the supraorbital cells) (1987:294). The codes of the two scans matched and the remains were determined to be those of the suspected man (Yoshino et al., 1987:295).

6. Marlin et al. (1991) present a series of cases where personal identification was resolved by comparison of the structure of the frontal sinus illustrated by cranial or dental radiographs. The first case was a burn victim whose identity could not be resolved by visual recognition. In this case there was quite distinctive dental work (gold thimbles on three of the remaining maxillary teeth) and postsurgical evidence (previous cleft palate and mandibular orthognathic surgery). Positive identification was based on dental radiographs and frontal sinus size and shape (Marlin et al., 1991:1766). In a second case the victim had also been extensively burnt, and the authorities suspected homicide and arson. A positive identification was made through the comparison of the frontal sinus outline on antemortem and post-mortem skull x-rays. In a third case a naked male body was retrieved from a river in such an advanced state of decomposition that visual identification was impossible. Six-year-old skull films were located belonging to the

suspected victim. The comparison of these films with post-mortem radiographs led to a positive identification based on the highly characteristic outline of the frontal sinuses (Marlin et al., 1991:1768). In the last case reported by Marlin et al., skeletonized human remains were discovered several months after this individual had been reported missing from an extended care facility. The assessment of the antemortem and post-mortem films provided positive identification (Marlin et al., 1991:1769). These cases described by Marlin et al., show that the morphology of the frontal sinus is an important key area for the resolution of unidentified decedents. These authors proved that this region is particularly useful in cases where the soft tissues of the body have been destroyed by fire or decomposition.

7. Owsley (1993) used radiographic comparison of the skull to resolve the identity of a journalist who went missing in Guatemala. Discovered remains were fragmentary and cremated, but there were several distinctive features represented on the radiograph including large orbits, and maxillary and frontal sinuses. The frontal sinus was asymmetrical, the right side being larger than the left, and with scalloped superior borders. In the midline and superior to the nasion running up the frontal was a well-defined groove fading as it approached the level of the hair line. This sulcus was narrow but clearly discernable on the antemortem x-ray where it overlapped with one lobe of the right frontal sinus. The area was represented in the postmortem remains by three fragments of the frontal bone, which could be pieced together to match the region seen on the antemortem x-ray. Owsley concluded that this case study illustrated that positive identification is still possible despite the extreme fragmentary and cremated condition of the human remains (Owsley, 1993:1381).

8. Angyal and Derczy, (1998) published three case studies which solve identity by using the comparison of ante and postmortem radiographs; however only one of these studies employed the frontal sinus. A decaying unidentified body was found in the summer of 1996. In an attempt to resolve personal identity medical records were sought. X-rays were located of the skull and nose taken due to trauma to this area. These were compared with corresponding radiographs of the same area. The outlines and edges of the frontal sinus, the cells, the contours of the eye sockets, and the edges of the nose bone positively linked the two in addition to the nature of the nasal break, confirming the identity of the decedent. The other case studies discussed by Angyal and Derczy matched ante- and postmortem radiographs of the pelvis and lumbar vertebrae and the authors remind us that "it is also important to bear in mind that we must be flexible when trying to resolve identity and base the assessment on the antemortem material available" (Angyal and Derczy, 1998:1089).

9. Nambiar et al. (1999) report on a case where they identified a badly burnt male victim from an air crash. Three antemortem radiographs were located and compared to postmortem radiographs; these confirmed the identity of the deceased.

10. Reichs and Dorion (1992) investigated a case report using computer tomography images. On May 15, 1990 the putrefied remains of a middle-aged white male were retrieved by the Canadian Coast Guard from the St. Lawrence River. The individual was endentulous, but still retained a complete set of upper and lower dentures. Although partially clothed there was no identification found with the body. The identity of the decedent was suspected and positive identification was made based on the similarities in maxillary sinus shape, and the details of the mandibular canal morphology and trabecular

bone (Reichs and Dorion, 1992:7). While identification was not based on the morphology of the sinus, Reichs and Dorion did use this case to test a methodology their article promotes. After taking post-mortem scans to match the level of the antemortem ones, the authors scored several characteristics of the frontal sinuses and found a high degree of congruency in this area between the two sets of scans.

11. While most of the case studies conducted using the frontal sinuses for identification have been in forensic anthropology, one case study was used on archaeological material. Costa (1978) used the height of the frontal sinus and sinus-transverse-cranial index to assess the remains purported to be those of Akhenaten. From the frontal sinus measurements, Costa concluded that the remains were male and did not have acromegaly (Costa, 1978:77).

All of the above cases represent instances where researchers have compared antemortem and postmortem images of the frontal sinuses captured on traditional plane film x-rays. With the advent of newer technologies, such as CT, some researchers have investigated whether the same comparison can be captured using this technology. The articles below are case studies that have resolved personal identity using CT captured images of the frontal sinuses.

12. Reichs (1993) reported on a second case study similar to the number 10 described above. A body of a white male was found partially decomposed and floating in the Lac St. Pierre. There was significant adipocere formation and the skull, hands and face were almost entirely skeletonized. Upper dentures were recovered, but the lower dentures were never found. Antemortem scans were discovered and the author carried out the Reichs-Dorion method to compare the morphology of the frontal sinus. A second

observer also scored the scans. Both observers agreed that the images represent the same individual (Reichs, 1993:161,166).

13. Haglund and Fligner (1993) discuss a case report where the body of a 77-year-old male was discovered in his home, four months after the last time he had been seen. Preliminary identification was made based on sex, age, race, and condition of the remains; however, visual identification could not be made because of animal scavenging damage. Identification could not be made using dental or fingerprints, but an antemortem CT scan was recovered. This was compared to a postmortem anterior-posterior radiograph. On the CT image at the level of the sella turcica and anterior cranial fossa a single air space was seen which investigators believed to be the right frontal sinus. There was no sign of the left frontal sinus on other slices of the CT scan. Similarly, the postmortem radiograph showed a corresponding unilateral right, single-celled, frontal sinus (Haglund and Fligner, 1993:709). In this case, comparison is between two different techniques of image capture, proving that this is possible.

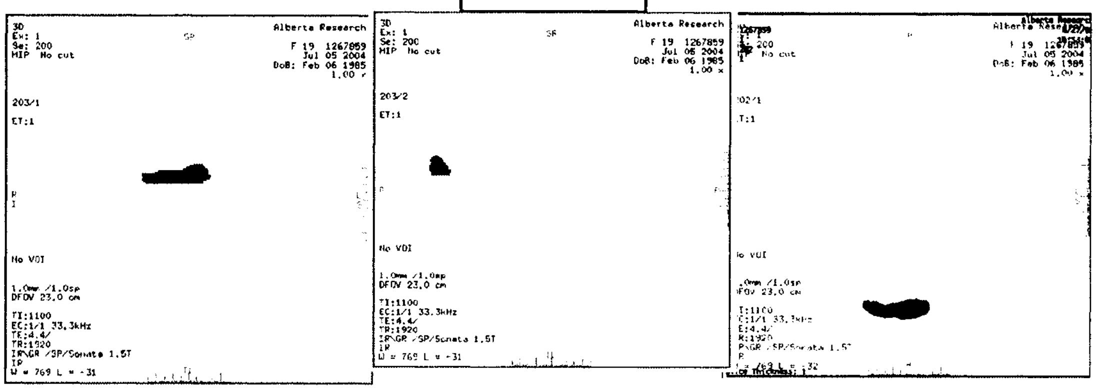
14. Smith et al. (2002) is the most recent publication using computerized tomography images of the frontal sinus to resolve personal identity. The only antemortem record available for the suspected individual was a CT scan of the head taken 9 days before the individual's disappearance. This was compared to a CT scan, taken in a similar position, of the cranium of an unknown individual. The authors report that the features of the frontal, mastoid and sphenoid sinuses, as well as the fine detail of the ethmoid air cells, are exactly the same in both scans. Multiple features of the sagittal suture and the overall bony detail of the calvarium are also similar, but these areas were felt by Smith et al. to

be less characteristic than the fine bony detail of the sinuses and mastoid air cells (Smith et al., 2002:938).

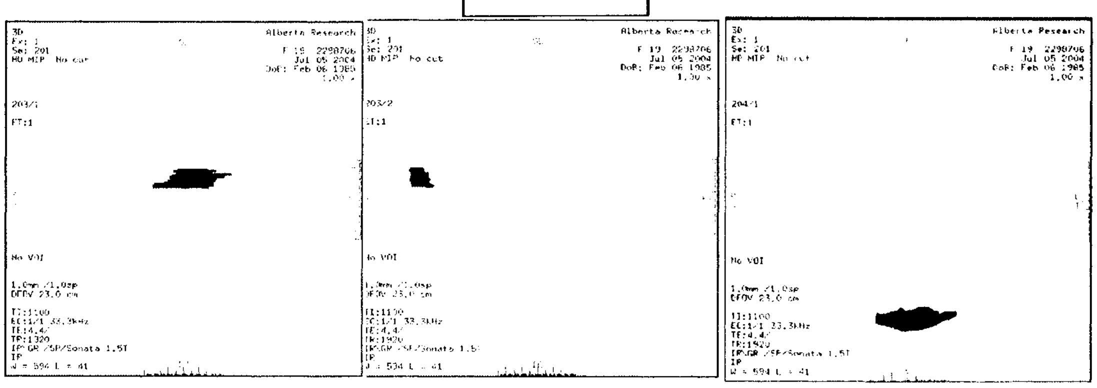
# Appendix Two - Screen capture images

This section presents the record of the anterior, lateral and superior images (respectively) of the frontal sinuses of the identical twins in my research sample. These images are screen captures obtained by tracing the outline of the frontal sinuses on contiguous axial images to produce a three-dimensional model.

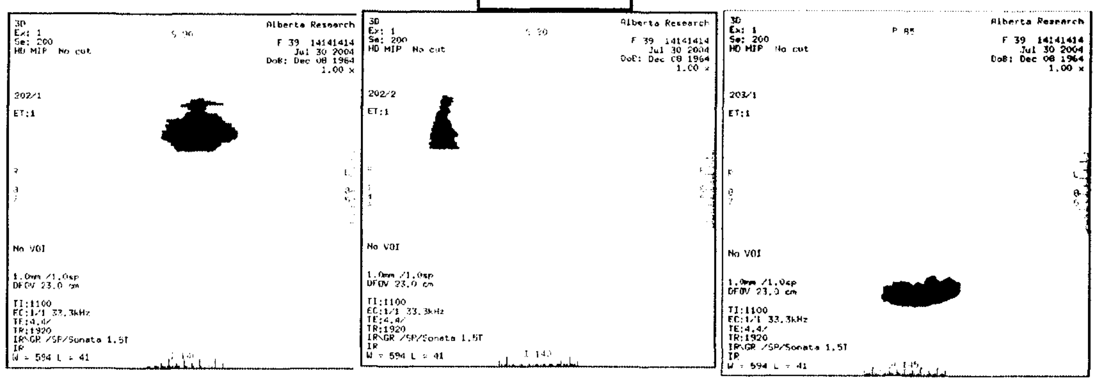
Twin A1



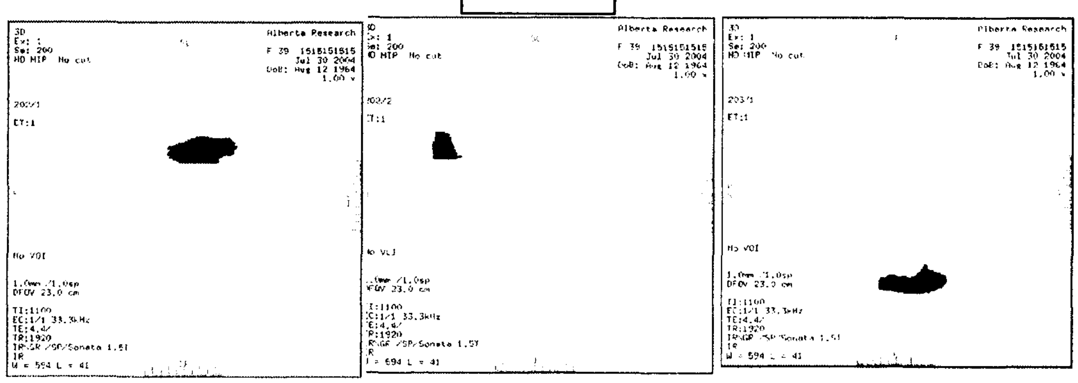
Twin A2



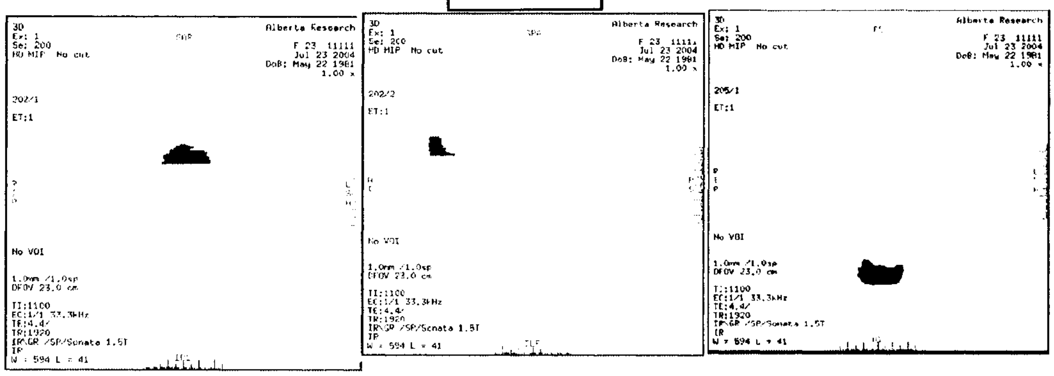
Twin B1



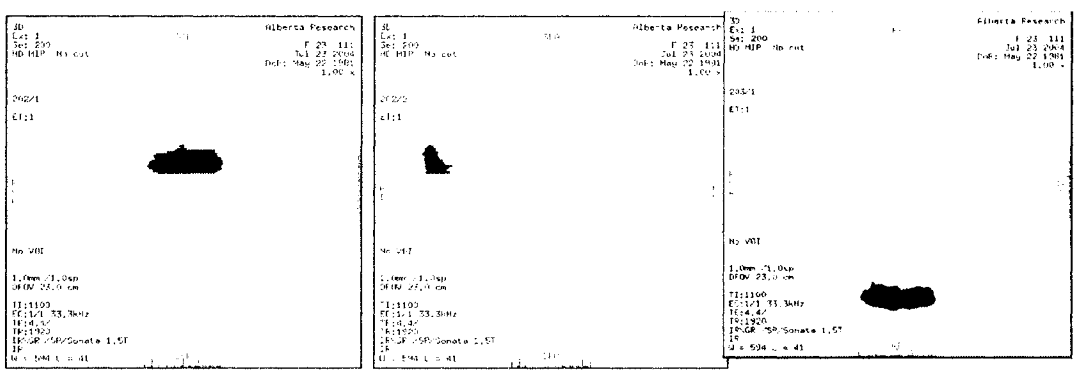
Twin B2



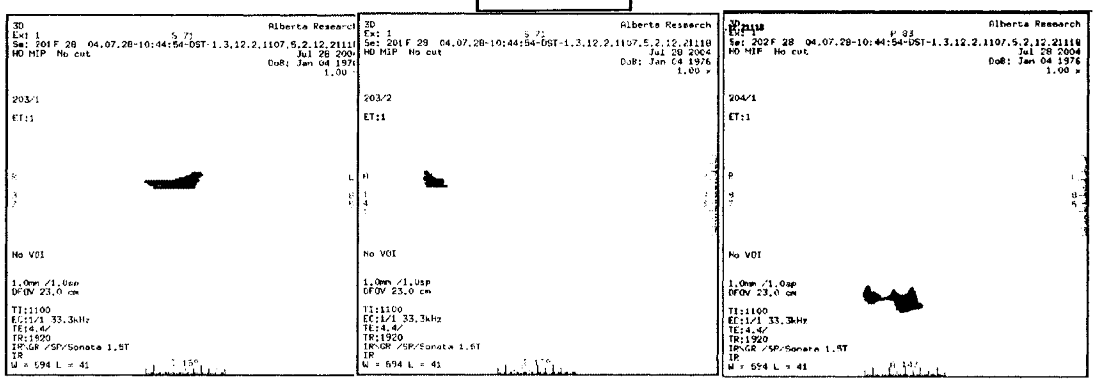
Twin C1



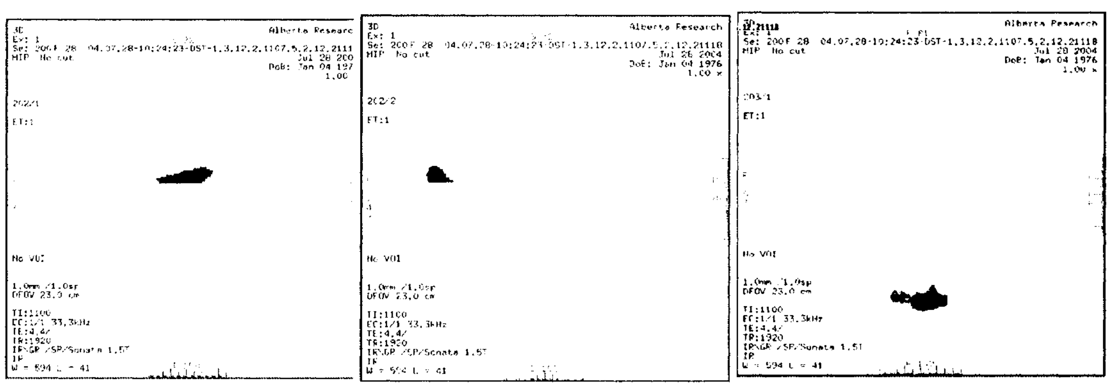
Twin C2



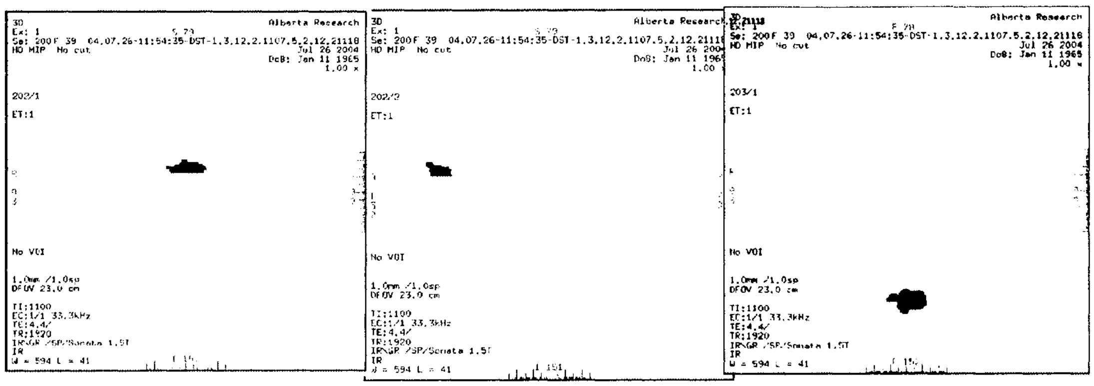
Twin D1



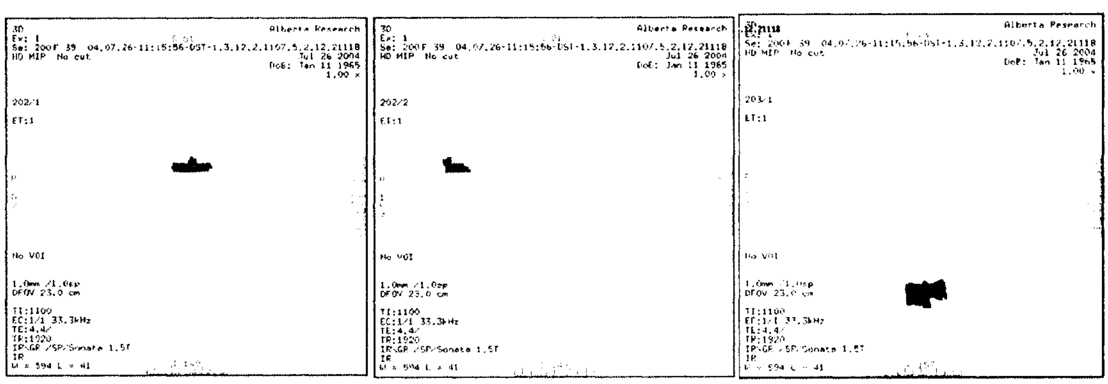
Twin D2



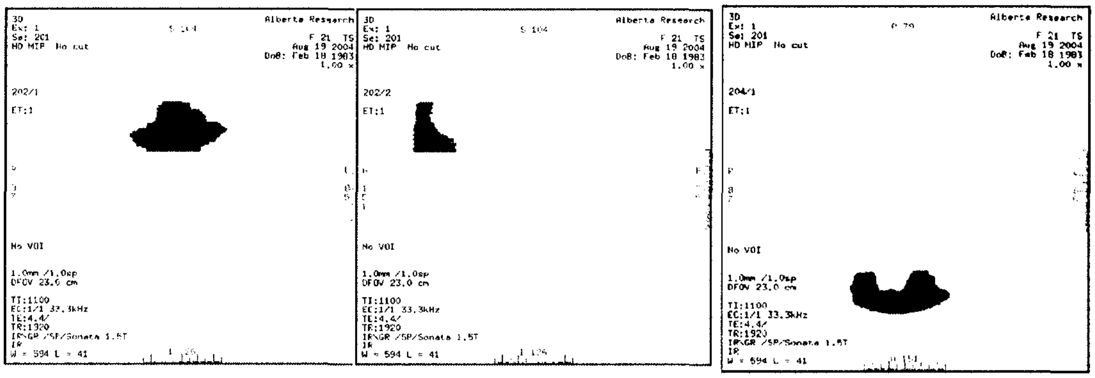
Twin E1



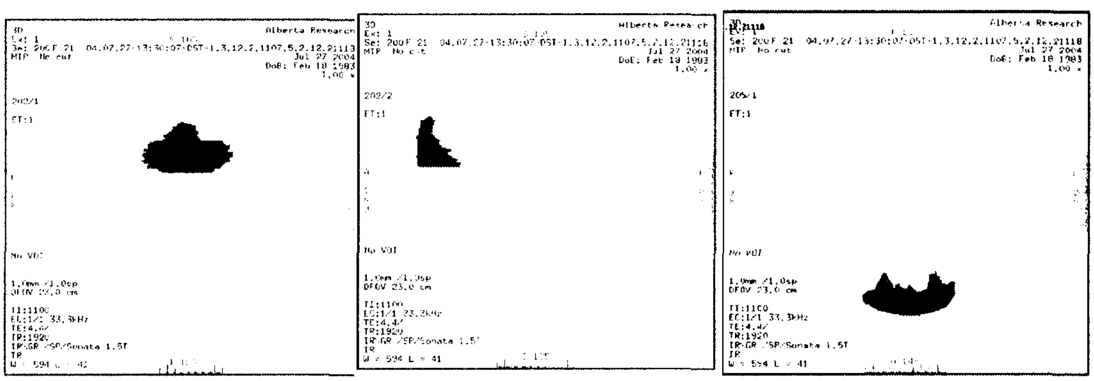
Twin E2



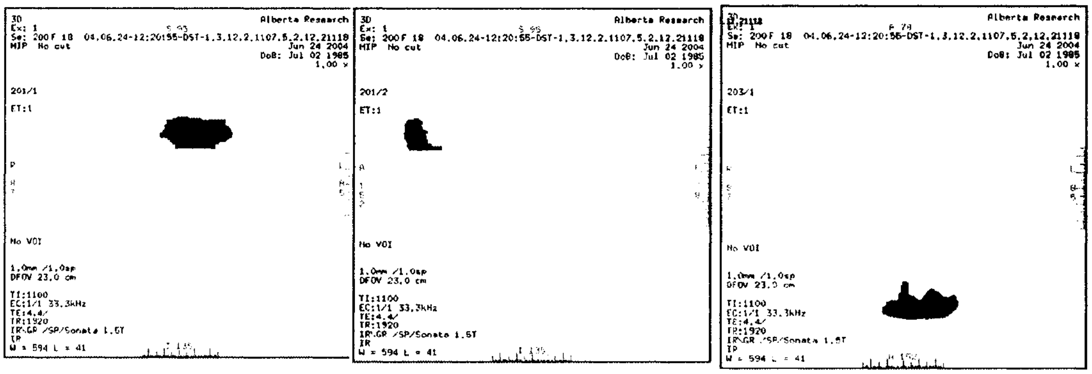
Twin F1



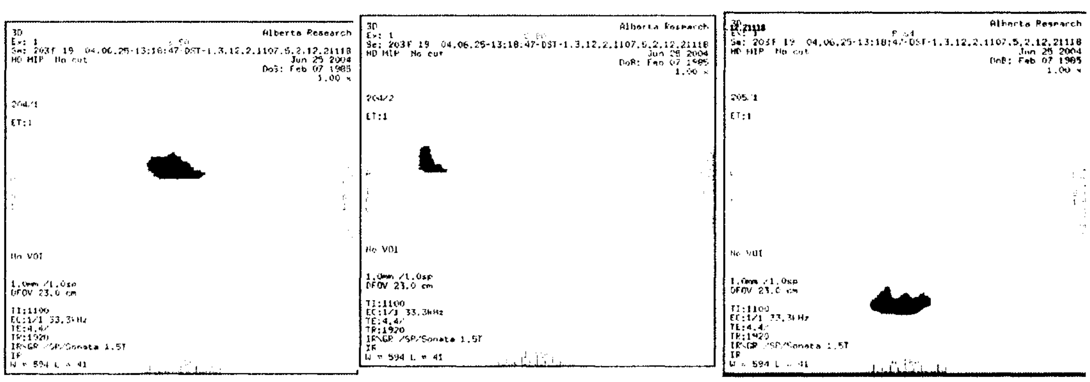
Twin F2



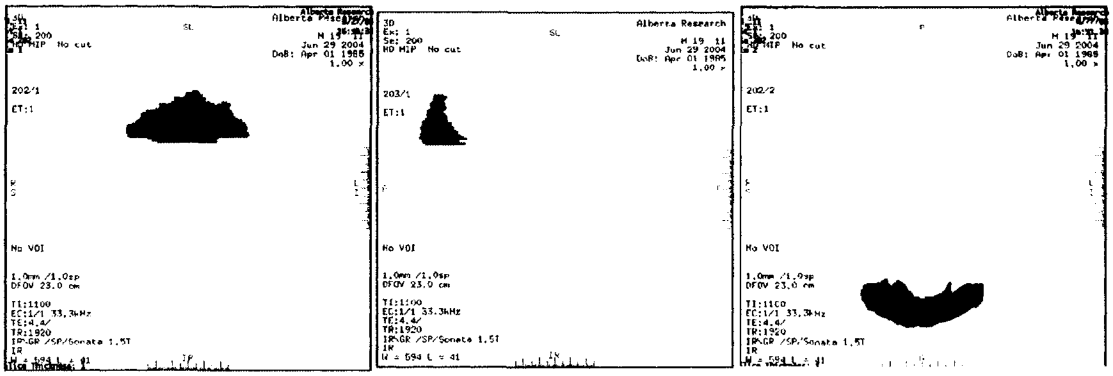
Twin G1



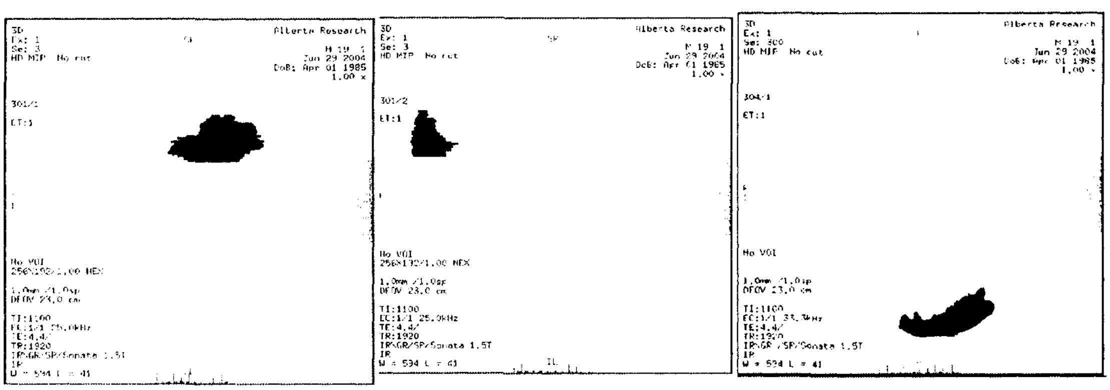

Twin G2



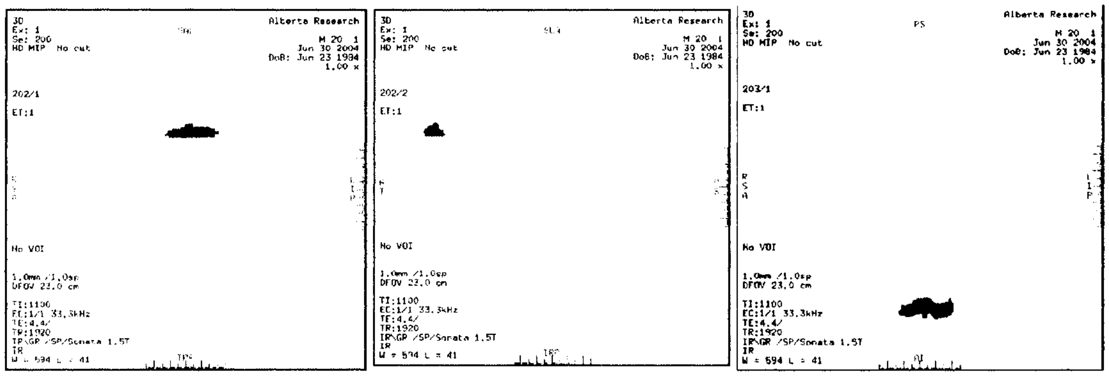
Twin H1



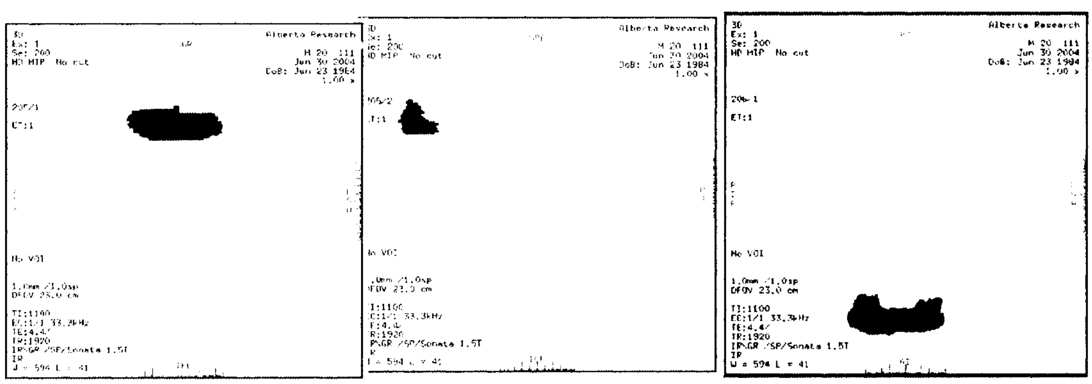
Twin H2



Twin I1



Twin I2



From these diagrams it is possible to make some rudimentary qualitative comments about the level of similarity between the sets of twins. For set A the twins have some similarity in terms of size, but are different in some aspects of shape. Twin set B are dissimilar in terms of size and shape, with twin B1 having larger sinuses. Likewise, twin set C are dissimilar in size and shape, with twin C2 possessing larger sinuses. Twin set D seem quite similar in regards to size, but there are some differences with regard to shape. Twin set E are very similar, especially when viewed in anterior and lateral images. Twin set F are very alike, particularly with regard to size. The shape of these twins' sinuses is also most similar when viewed in the anterior and lateral images. Twin set G do not appear to be overly similar; there is some difference in both shape and size of the sinuses of these twins. Twin set H are also somewhat dissimilar. Twin H2 has a larger left sinus, whereas twin H1 has more equal left and right sinuses. There also appears to be some difference in regards to size. Lastly, twin set I are very different with regard to size, with twin I2 having much larger sinuses. However, the difference would appear to be mostly related to size, since there are some similarities in shape, especially in the anterior images. This conclusion is corroborated by the results from the analysis of axial images seen in Tables 5 and 6. The axial images suggest that twins I1 and I2 have a similarity in overall shape, suggesting the volume difference seen in this pair is mainly due to size.