The Journal of Laryngology & Otology (2009), ***123***, *4–8*.

doi:10.1017/S0022215108003976

Review Article

Why do we have paranasal sinuses?

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Abstract

Introduction: The paranasal sinuses, comprising the frontal, maxillary, ethmoid and sphenoid sinuses, have caused consternation and debate over their true function over the course of nearly two millennia. This review aims to define the current evidence for the role of the paranasal sinuses, and to attempt to propose an answer to the question 'why do we have paranasal sinuses?'

Materials and methods: A literature review was conducted, searching Medline (1966–2007), Embase (1988–2007), the Cochrane Library and Ovid (1966–2007). Combinations of the following search terms were used: 'paranasal sinuses', 'physiology', 'anatomy', 'function', 'evolution' and 'rhinology'. Any relevant references were cascaded to increase detection of pertinent information. The current, tenable theories identified in the literature review are discussed and the evidence for them critically analysed.

Results: The current, tenable theories are described.

Discussion: The paranasal sinuses may act simply to improve nasal function; certainly, it has been demonstrated that they may act as an adjunct in the production of nitric oxide and in aiding the immune defences of the nasal cavity. However, there is a distinction between utility and evolutionary origin. It may still be that the sinuses arose as an aid to facial growth and architecture, or persist as residual remnants of an evolutionary structure with an as yet unknown purpose, and in doing so have found an additional role as an adjunct to the nasal cavity.

Key words: Paranasal Sinuses; Anatomy; Physiology

Introduction

The paranasal sinuses comprise the frontal, maxillary, ethmoid and sphenoid sinuses. They have caused consternation and debate over their true function over the course of nearly two millennia. As stated by Wright,[1] Vesalius[2] and Fallopius,[3] Galen[4] (130–201 AD) is credited with the first acknowledgement of their existence. However, Wright[1] himself found no direct reference to the sinuses in Galen's *De Usu Partium*.[4] Flottes *et al.*[5] attribute their discovery to Leonardo Da Vinci[6] (1452–1519). Both Kemp[7] and Pevsner[8] note that in Da Vinci's classic illustrations 'Two views of the skull', circa 1489, the frontal and maxillary sinuses are identified (see Figure 1). These sinuses may also be seen in Da Vinci's 'View of a skull', circa 1489 (see Figure 2). Da Vinci even proposed his own theory that the maxillary sinus 'contains the humor which nourishes the teeth'.[9]

Wright[1] considered that Fallopius[3] made the first contribution to paranasal sinus ontogeny with his observation that the sinuses were not present in the neonatal skull. Nathaniel Highmore (1614–1685) made further progress in understanding sinus development with a detailed description of the maxillary sinuses, in 1651; he also advanced the concept of their pneumatisation.[10]

Blanton and Biggs[11] document the fact that, throughout history, speculation over the role of the paranasal sinuses has been numerous and diverse. They recognised that much of this speculation arose from a 'basis of opinion rather than rigorous scientific investigation'. Blaney[12] considered that no conclusive theory to explain their *raison d'être* had yet been found.

Materials and methods

In order to define the current evidence for the role of the paranasal sinuses and to attempt to propose an answer to the question 'why do we have paranasal sinuses?', a literature review was conducted, searching Medline (1966–2007), Embase (1988–2007), the Cochrane Library and Ovid (1966–2007). Combinations of the following search terms were used: 'paranasal sinuses', 'physiology', 'anatomy', 'function', 'evolution' and 'rhinology'. Any relevant references were cascaded to increase detection of pertinent information. The current, tenable theories identified in the literature review are discussed below and the evidence for them examined.

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Accepted for publication: 18 August 2008. First published online 28 October 2008.

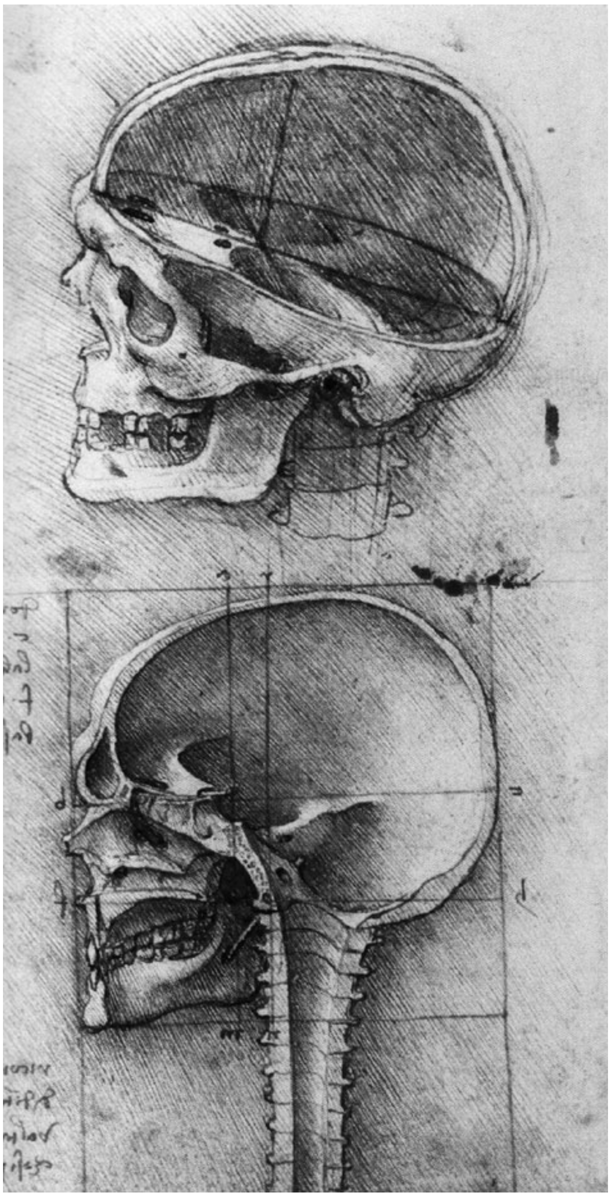

FIG. 1
'Two views of the skull' by Leonardo Da Vinci, circa 1489.

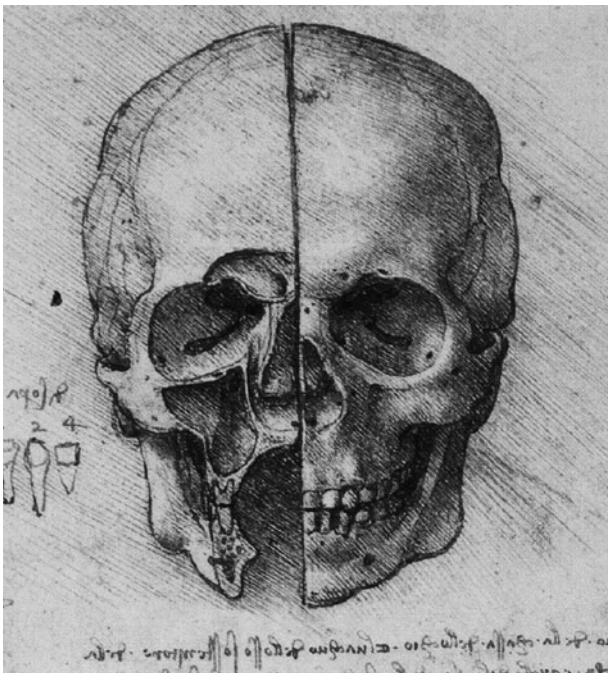

FIG. 2
'View of a skull' by Leonardo Da Vinci, circa 1489.

Results and analysis

Imparting resonance to the voice

The paranasal sinuses' function of imparting resonance to the voice was first proposed by Bartholinus[13] in the seventeenth century; he noted that they were not present in those of 'faulty voice'. Several authors[14,15] supported this theory; Howell[16] studied the Maori people of New Zealand and observed 'peculiarly dead voices' in those with 'an underdevelopment of their accessory sinuses'. He therefore proposed that 'the peculiar quality or timbre of the individual voice arises from the accessory sinuses and the bony framework of the face'. Wegner[17] also supported this theory, observing that howling monkeys had large sinuses.

However, Proetz[18] questioned this theory, noting that lions had small sinuses but comparatively loud voices. Furthermore, the guinea pig and giraffe, with their relatively quiet or shrill, irresonant voices, were noted to have large sinus cavities.[19] Negus[20] demonstrated, through a comparative anatomy study, that there was no relation between the presence or absence of the paranasal sinuses and the voice. Flottes *et al.*[5] and Schaeffer[21] also remarked on the physical qualities of the paranasal sinuses which made them poor resonators, noting: the limited size of the ostia; the covering of the ostia by the turbinates; the closed nature of the cavities; and the covering of the sinus walls, dampening any vibration. It has also been observed that, following sinus surgery, no modification of the voice occurs.[5] Flottes *et al.*,[5] Blanton and Biggs[11] and Blaney[12] all concur that this theory is unsound.

Humidifying and warming inspired air

Air exchange is known to take place in the sinuses during respiration.[22,23] However, the amount of exchange that is thought to occur is negligible.[5,18,20,23] Negus[20] considered the process of humidification and warming of inspired air in species requiring the greatest degree of warming 'takes the form of an elaborately branching maxillo-turbinal body' rather than depending on the paranasal sinuses. He noted that 'it is more profitable to have large maxillo-turbinal bodies, filling the anterior part of the snout, than hollow air spaces'. Levine and Clemente[24] note that, during a single respiratory act, only one-thousandth of the air volume of the sinuses is exchanged, and that the air in the maxillary sinuses is not exchanged even after five minutes of normal breathing.[25] Given the lack of any meaningful air exchange into the sinuses, several authors have doubted that this process

https://doi.org/10.1017/S0022215108003976 Published online by Cambridge University Press

occurs and have considered this theory flawed.[5,11,12,18,20]

Increasing the olfactory area

Cloquet[26] proposed in 1830 that human maxillary sinuses were lined with olfactory epithelium, and therefore suggested that their role might be to increase the area of the olfactory membrane. However, this mucous membrane was later found to be lined by non-olfactory epithelium,[27] and this theory has been roundly dismissed.[11,12]

Providing thermal insulation to vital parts

The possible role of the paranasal sinuses in providing thermal insulation to vital parts was originally proposed by Proetz.[18] He likened the sinuses to 'an air-jacket about the nasal fossae closely resembling the water jacket of a combustion engine'. However, Eskimos often possess no frontal sinuses,[28,29] while Africans possess large frontal sinuses.[30,31] Rae *et al.*[32] demonstrated that Japanese macaques, which show intraspecies variability, have smaller sinuses in individuals from colder areas. Thermal insulation as a primary role for the paranasal sinuses therefore seems unlikely.

Absorbing trauma to protect the sensory organs

Negus[20,33] first proposed that the sinuses might absorb trauma in order to aid protection of the sensory organs, after noting air spaces extending over the cranial vault and into the hollowed horns of ungulates. However, he also noted that some ungulates, notably the elk and moose, did not possess these air spaces but nevertheless sustained high impact trauma without obvious damage. Riu *et al.*[34] viewed the sinuses as a pyramid, with the base situated anteriorly and the apex at the sphenoid sinus, producing an architectural structure suited to protecting the endocranium. Blaney[12] considered the proposal significantly weakened due to interspecies variability, whereby those species appearing to suffer high impact trauma to this area had very small sinuses.

Aiding facial growth and architecture

Proetz[35] proposed that the human frontal and maxillary sinuses might be designed to assist forward and downward growth of the face; 'in consideration of the rearrangement of the face structure it becomes apparent that the formation of the sinuses is necessary for the surrounding parts'. He also stated that the 'frontal sinuses develop... along with advancement of the face; the maxillary grows... with the growth of the jaw; the sphenoid... with the broadening of adjacent parts', such that the development of the sinuses ceases when an adult age is attained, at which time the craniofacial structures acquire a definitive form. However, Negus[20] noted that individuals with a single frontal sinus of minute volume did not show deficient facial growth. Galperin[36] attributed the presence of the sinuses to strains and stresses on the skull due solely to the chewing apparatus, while Eckel[37] considered that 'the bite and chewing function are the forces which determine the size and development of the maxillary sinus'. This would not however explain the presence of other paranasal sinuses, and *in vivo* experiments using strain gauges in primates suggest that little stress reaches the frontal sinus region.[38,39]

Takahashi[40] considered that the sinuses originally developed as an aid to olfaction and subsequently altered following the evolution of mammals from primate to human, with consequent retraction of the maxillo-facial massif and cerebral enlargement. It was further proposed that the paranasal sinuses in humans arose as the result of an increase in the angle between the forehead and the frontal cranial base and a decrease in the angle of the cranial base at the sella turcica.

Evolutionary remnants

Negus[20] stated that 'there does not appear to be any functional reason for the appearances of air spaces, and the irregularity of their distribution, often with complete absence, suggests that they are only unwanted residual spaces'. Rae and Koppe[41] observe that the maxillary sinuses are 'the taxonomically most widespread paranasal pneumatisation'. They note that they are present in many groups of mammals[42] and were probably present in the last common ancestor of eutherians.[43] The maxillary sinuses were then retained in many anthropoids,[44–47] including humans. Rae and Koppe suggest finally that their presence requires 'no additional explanation; these organisms possess the sinus because their ancestors did'.

Lightening the skull bones to maintain equipoise of the head

The theory that the sinuses developed as an aid to maintaining balance of the head has been proposed by several authors.[2,4,6,10] However, Braune and Clasen[22] calculate that if the sinuses were instead composed of spongy bone, then a 1 per cent increase in the weight of the head would result; they consider this a negligible amount. Furthermore, an electromyographic investigation of the neck musculature's response to loading of the anterior aspect of the head concluded that the paranasal sinuses are not significant as weight reducers of the skull for the maintenance of equipoise.[48]

Flotation device

Both Hardy[49] and Evans[50] have suggested that the sinuses may act as a flotation device. Hardy[49] proposed that *Australopithecus* represented the link between *Homo habilis* and *Homo sapiens* and anthropomorphic monkeys. *Australopithecus* was thought to be cut off from the African mainland 6.5 million years ago. Forced to adapt by natural selection, the monkeys developed the paranasal sinuses as flotation devices to allow maintenance of the cephalic part and therefore to maintain the nasal cavities out of water. However, Rae and

Koppe[41] note that the same group of sinuses occur in all African apes, and they consider it extremely unlikely that an aquatic way of life was the selective evolutionary pressure behind this. The same authors,[41] citing Gould and Vrba,[51] comment that an important distinction needs to be drawn in the study of 'function' between utility and evolutionary origin. They state that 'while a structure may permit a particular behaviour in an extant organism, this is no guarantee that this function was responsible for the original evolution of the trait'.

Secreting mucus to moisten the nasal cavity

This theory, advocated by Haller,[52] has now been dismissed on the basis of histology,[53] which shows that the sinuses have only 50–100 submucosal glands, in contrast to the nose with its 100 000 glands. It is therefore suggested that the sinuses cannot secrete a meaningful amount of mucus. Ballenger[54] noted that the mucus from the sinuses is 'uncontaminated', and proposed an alternative role whereby the sinus mucus might dilute inspired contaminants in the nasal mucus.

Aiding nasal cavity immune defence and production of nitric oxide

The paranasal sinuses are known to play a role in strengthening immune nasal function, with the additional production of immunoglobulins and lythic enzymes (such as lisozyme) which destroy peroxidases and the peptidoglycans of bacterial cell walls.[24] Mucociliary clearance into the nasal cavity could then bolster nasal immune defences.

Nitric oxide has been proven to be generated by both the paranasal sinuses and the nasal cavity.[55,56] Furthermore, the sinuses are capable of generating high concentrations of NO, of greater than 20 parts per million,[56] and higher concentrations still are generated in the nasal cavity.[57] The importance of NO in this area is thought to be twofold, involving both inhibition of viral and bacterial growth and upregulation of ciliary beat frequency.[55] It may therefore be that the paranasal sinuses act as an adjunct in providing the nasal cavity with NO.

Discussion

Theories of the possible role of the paranasal sinuses generate both controversial and complex issues. While some of the older theories may be easily dismissed, others seem frustratingly difficult to either confirm or refute, partially due to a lack of relevant, hard evidence. The most recently proposed theories have at least been exposed to the rigour of scientific investigation, allowing us perhaps to edge towards a possible, acceptable explanation of paranasal sinus function.

Levine and Clemente[24] believe that the paranasal sinuses may act simply to improve nasal function; certainly, it has been demonstrated that they may act as an adjunct in the production of NO and in aiding the immune defences of the nasal cavity. While this would give the paranasal sinuses a role, and proves at least that they are not, as was once thought, without function,[20] it might not necessarily answer the question 'why do we have paranasal sinuses?' As previously stated, when considering function there is a distinction between utility and evolutionary origin.[51] It may still be that the sinuses arose as an aid to facial growth and architecture, or that they persist as residual remnants of an evolutionary structure with an as yet unknown purpose, and in doing so have found an additional role as an adjunct to the nasal cavity.

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Mr J Keir takes responsibility for the integrity of the content of the paper.
Competing interests: None declared