Hypothesis: Cranial Suture Complexity is Influenced by Sensory Innervation

Charles S Masarsky

Narrative: Recognition of the significance of the mobility implied by cranial sutural patency is one of the underpinnings of Chiropractic and osteopathic clinical techniques for the cranium.

Given the influence of respiratory muscles on sutural complexity, certain breathing exercises may be found to promote sutural complexity. More generally, any interventions to optimise breathing such as respiratory therapy, Chiropractic adjustments, and osteopathic manipulation could be advantageous in this regard.

I describe factors affecting the development of cranial sutures and propose the hypothesis '*Cranial suture complexity is influenced by sensory innervation*' and suggest ways in which this can be clinically examined.

Indexing terms: Chiropractic; cranial sutures; comparative anatomy; breathing therapies; cranial treatment.

Cranial Suture Complexity

Cranial sutures are collagen-rich fibrous connections modified from the periosteal tissues of adjacent cranial bones. If persistence is a measure of significance, cranial sutures are significant indeed.

A computerised tomography (CT) study of 77 human skulls concluded: '*Although there is an association between increasing adult age and gradual closure of the sagittal, coronal, and lambdoid sutures, complete obliteration of these sutures rarely occurs. Even in patients aged 100 or older, most sutures apart from the metopic remained patent*'. (Soliman et al, 2023)

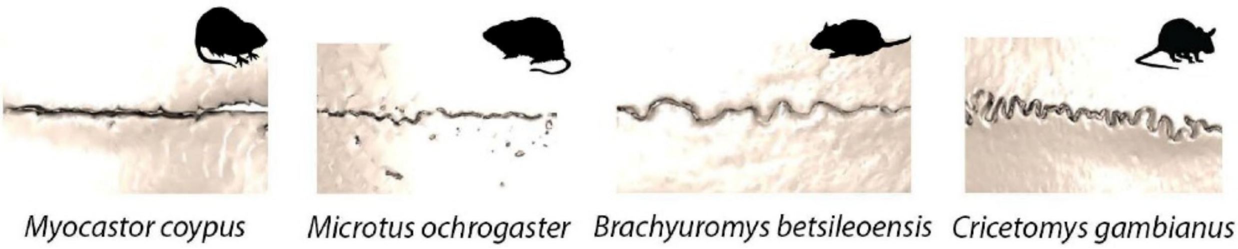
> *... It is entirely plausible that therapies directed as clinically indicated to normalise perceived cranial dysfunctions are a viable and valuable therapeutic intervention ...'*

Recognition of the significance of the mobility implied by cranial sutural patency is one of the underpinnings of Chiropractic and osteopathic clinical techniques for the cranium. The development of these techniques was underway by the 1920s and well-known within both professions by the 1930s. (Cottam, 1936; Sutherland, 1939)

A cranial suture does not follow a simple straight pathway like a canal. Its pathway resembles the complex journey of a wildly meandering river. Just as a river is shaped by adaptation to the uneven demands of the terrain, the complex pathway of a suture is shaped by stresses impacting the cranium.

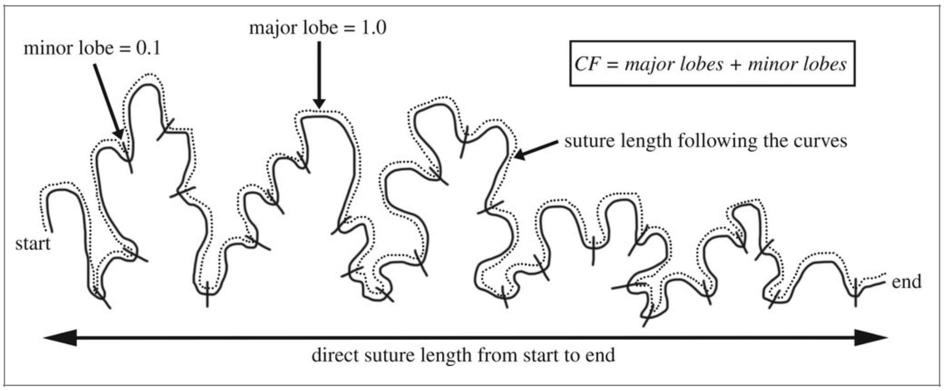
These stresses include passage through the birth canal, the expansion required by the growing brain, trauma, the mechanics of respiration, and the forces of mastication. (Lesciotto and Richtsmeier, 2019) The importance of mastication forces in the development of sutural complexity was apparent in a 2021 paper. (White et al 2021). Figure 1 illustrates the sagittal sutures of four related rodent species. The difference in complexity is immediately apparent. The authors attribute this to the different diets of these species. This comports with the findings of a 2018 study of mice of the same species on different diets. (Byron et al 2018) The authors found that 'chewy' diets are associated with more complexity than soft diets. Based on mechanical and comparative anatomy considerations, Byron et al maintain that sutural complexity is a way of dampening the stresses generated by the muscles of mastication by redirecting the strain in multiple directions.

Figure 1: Sagittal suture morphological variation in four species of rodent: Myocastor coypus (coypu); Mircotus ochrogaster (prairie vole); Brachyuromys betsileoensis (Be tsileoshort-tailed rat); Cricetomys gambianus (Gambian pouched rat). (From: White et al, 2021)



Sutural complexity can be measured in a number of ways. The most intuitively understandable measurement is the sutural complexity index (SCI). In this measurement, the length of the suture is divided by the straight-line distance between the two endpoints (Figure 2). The greater the SCI, the greater the complexity. SCI and other complexity metrics are generally calculated with the help of a (CT) imager equipped with an appropriate algorithm.

Figure 2: Sutural complexity index (SCI) = suture length following the curves divided by direct suture length from start to end (From: White et al, 2020)



The importance of sutural complexity lies in the increased flexibility it confers on the cranium. This flexibility helps protect the brain during traumatic brain injury (TBI). Interestingly, Zambrano et al found the presence of Wormian (intrasutural) bones to protect the brain during skull impacts (Zambrano et al, 2021). The presence of bones within a suture can be thought of as a form of sutural complexity.

The Hypothesis

It is widely believed that the development of complexity is governed entirely by the activity of osteoblasts and osteoclasts lining the margins of the sutures and/or signalling from cells within the connective tissue matrix of the sutures themselves. For example, Roth et al discuss the importance of non-motile cilia as mechanosensory structures at the cellular level. (Roth et al, 2022) While the stresses influencing the sutures are undoubtedly detected by non-neural cells entirely intrinsic to the sutures themselves, that does not rule out the role of sensory innervation with potential to interact with intrinsic cells in the development of sutural complexity. I therefore propose this hypothesis:

> Cranial suture complexity is influenced by sensory innervation.

Sutural innervation

Zhao and Levy found the cranial periosteum of rats to be sensitive to mechanosensitive as well as nociceptive stimuli (Zhao and Levy, 2014). This periosteal innervation is provided by branches of the trigeminal nerve, and courses through the sutures of the calvarium.

It is not clear whether mechanoreceptive nerve endings from these branches terminate within the tissue of the sutures. However, the collagen fibres of the sutural connective tissue clearly terminate on the mechanosensitive periosteum of the adjacent bones. Therefore, the sutural connective tissue receives sensory innervation from the trigeminal nerve, directly or indirectly.

In this regard, Tower et al found cranial sutures in mice to require sensory innervation for early development. (Tower et al, 2021) When sensory nerve growth into sutural tissue was inhibited, activity of proliferative cells was reduced, leading to premature suture closure.

Testing the Hypothesis

While the above observations are suggestive, direct evidence of sensory nerve involvement in human sutural complexity awaits further research. One set of approaches could focus on asymmetric sensitivity of trigeminal afferentation. Left-right differences in trigeminal sensation would be expected to correlate with asymmetrical sutural complexity. This could come about as a result of the sorts of trauma that result from whiplash injuries and concussions.

The common involvement of the upper cervical spine in such injuries could disturb the trigeminocervical complex of the upper spinal cord. The effect of such injury is frequently unilateral. Suture complexity index measured on CT scan at presentation would be compared with complexity after recovery. Alternatively, patients with chronic untreated upper cervical dysfunction could be compared with the recipients of early successful intervention.

Especially revealing would be complexity measurement of the bilateral sutures of the calvarium: the coronal and squamosal sutures. The zygomatic bone would merit attention as well where it interacts with the calvarium at the zygomaticotemporal

and zygomaticofrontal sutures.

Of course, such a study could be confounded by the mixed nature of the trigeminal nerve. Any influence on sutural complexity could be a result of motor influence on the muscles of mastication. Therefore, care would have to be taken to observe patients with hemicranial anaesthesia or hypaesthesia whose trigeminal motor function is intact. If both motor and sensory deficit are involved, it could be seen whether the increase in sutural complexity was more closely correlated to change in motor or sensory function.

A more long-lasting asymmetry in trigeminal function afflicts victims of certain disease processes. For example, trigeminal asymmetry sometimes progresses to the point of hemicranial numbness in stroke and diabetic neuropathy. The aforementioned sutures could be studied for indications of complexity asymmetry in these patients. The aforementioned care would have to be taken to eliminate or at least reduce the confounding influence of altered trigeminal motor function.

In addition to the impact of trigeminal sensory deficit on sutural complexity, the effect of trigeminal sensory stimulation could be studied as well. For example, the Pacinian corpuscles are sensitive to both deep pressure and vibration. Therefore, vibration in the frequencies detectable by these mechanoreceptors, primarily100 to 2,000 Hz according to Chen et al, would presumably stimulate some of the same neurological pathways as the sort of deep pressures that would tend to affect the intrinsic cells of the sutures. (Chen et al, 2025) Therefore, exposure to these vibration frequencies may offer a way of stimulating sensory pathways relevant to sutural complexity without traumatising the skull with compression or distraction.

To take advantage of this for hypothesis testing, a useful group to study would be musical performers. Undoubtedly, orchestra conductors, brass and woodwind instrumentalists, and vocalists experience frequent vibration at frequencies detectable by Pacinian corpuscles. While I was unable to locate a report of Pacinian corpuscles within the intrinsic sutural tissue, they are abundant in the overlying dermis of the scalp and are also present in the periosteum of adjacent cranial bones. If sutural complexity in musical performers is greater than that in control subjects, that would add support to the hypothesis.

Along similar lines, people in Eastern religious communities such as some Buddhist monks engage in long periods of chanting. The vibrational stimulation to sensory innervation related to the cranial sutures would probably be similar to that of musical vocalists. It is also possible that the vibrational frequencies of some electric toothbrushes are in the range detected by Pacinian corpuscles. However, the daily exposure to this vibration may be too brief to affect sutural complexity.

Implications of the Hypothesis

If the hypothesis is supported, maintaining the integrity of sutural innervation would be expected to facilitate normal complexity development. Since complexity confers resilience in the face of future trauma, any measures to support related neurological fitness would seem indicated. It is possible that osteopathic and Chiropractic cranial intervention can stimulate the development of sutural complexity. In terms of the hypothesis however, it would be problematic to determine whether the impact on complexity was due to sensory stimulation or mechanical stimulation of the intrinsic sutural tissues.

As mentioned above, trigeminal nerve function can be disturbed by upper cervical dysfunction. Therefore, Chiropractic adjustments, osteopathic manipulation, and physical therapy directed at correcting cervical dysfunction could be helpful in promoting optimal sutural complexity. This would be especially important for victims of head trauma, since increased complexity would help protect the brain during future trauma.

In addition to supporting normal trigeminal nerve function, timely care of cervical dysfunction would be expected to aid the physiology of the connections between the dura mater and the tissues of the vertebra column, the myodural bridge. Recent findings suggest that the myodural bridge facilitates the normal flow of cerebrospinal fluid. (Xu et al, 2016) Given that sutural complexity is influenced by the internal mechanics of the growing brain, it is plausible that this complexity is also influenced by variations in CSF flow, with the concomitant variations in intracranial pressure. It would not be surprising if the suboccipital muscles that govern myodural tension were found to be responsive to changes in CSF flow. This could have an indirect effect on sutural complexity.

Given the influence of respiratory muscles on sutural complexity, certain breathing exercises may be found to promote sutural complexity. More generally, any interventions to optimise breathing such as respiratory therapy, Chiropractic adjustments, and osteopathic manipulation could be advantageous in this regard. The mechanics of breathing are of course influenced by sensory input from many structures, such as the diaphragm, intercostal muscles, and the peripheral chemoreceptors.

Forces generated by the muscles of mastication are important in sutural complexity development. The sensory input from mechanoreceptors related to the TMJ would influence the motor components of mastication. Therefore, timely correction of TMJ dysfunction via chiropractic, osteopathic, and dental care are expected to be of help.

Certain behaviours undoubtedly generate forces that influence cranial suture development. Examples would include facial expressions, thumb sucking, head rubbing, and hair pulling. These behaviours can be habitual or responses to head pain or discomfort. They can also be responses to more general emotional stress. It may be possible to identify which behaviours are beneficial for the development of sutural complexity. Exercises currently within the domain of speech therapy may be helpful here.

As discussed in the section on testing the hypothesis, vibration may stimulate sensory pathways relevant to sutural complexity. If the hypothesis is supported, vibration protocols could be developed to provide non-traumatic stimulation of sutural complexity. Such protocols could be used prophylactically for athletes or workers exposed to frequent head trauma. The protocols also may be included in the rehabilitation of head trauma victims by building resilience to future injuries.

Conclusion

The cranial sutures are living structures, richly innervated. It is entirely plausible that therapies directed as clinically indicated to normalise perceived dysfunctions are a viable and valuable therapeutic intervention.

Charles S Masarsky

DC

Northern Virginia Community College

Private practice of Chiropractic, Vienna VA

viennachiropractic@verizon.net

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References

Byron CD. Role of the osteoclast in cranial suture waveform patterning. Anat Rec A Discov Mol Cell Evol Biol. 2006 May;288(5):552-63. DOI 10.1002/ar.a.20322.

Chen Y-T, Wagner DDT, Loutit AJ, et al. .Lamellar Schwann cells in the Pacinian corpuscle potentiate vibration perception.Sci. Adv.11,eadt5110(2025).DOI:10.1126/sciadv.adt5110

Cottam NL. The Story of Craniopathy: A Science of Health, Its Theory and Practice. Cottam, Los Angeles, 1936.

Lesciotto KM, Richtsmeier JT. Craniofacial skeletal response to encephalization: How do we know what we think we know? Am J Phys Anthropol. 2019 Jan;168 Suppl 67(Suppl 67):27-46. DOI 10.1002/ajpa.23766.

Roth DM, Souter K, Graf D. Craniofacial sutures: Signaling centres integrating mechanosensation, cell signaling, and cell differentiation. Eur J Cell Biol. 2022 Jun-Aug;101(3):151258. DOI 10.1016/j.ejcb.2022.151258. Epub 2022 Jul 28. PMID: 35908436.

Soliman L, Ahn S, Hunt V, et al. Gaining Closure: Do Cranial Sutures Fuse at Reported Age Ranges? Plast Reconstr Surg Glob Open. 2023 May 22;11(5):e5013. DOI 10.1097/GOX.0000000000005013.

Sutherland WG. The Cranial Bowl: A Treatise Relating to Cranial Articular Mobility, Cranial Articular Lesions and Cranial Technic. Free Press Company, Mankato, Minnesota, 1939.

Tower RJ, Li Z, Cheng YH, Wang XW, et al. Spatial transcriptomics reveals a role for sensory nerves in preserving cranial suture patency through modulation of BMP/TGF-β signaling. Proc Natl Acad Sci U S A. 2021 Oct 19;118(42):e2103087118. DOI 10.1073/pnas.2103087118.

White HE, Clavel J, Tucker AS,et al. A comparison of metrics for quantifying cranial suture complexity. J R Soc Interface. 2020 Oct;17(171):20200476. DOI 10.1098/rsif.2020.0476. Epub 2020 Oct 7.

White HE, Goswami A, Tucker AS. The Intertwined Evolution and Development of Sutures and Cranial Morphology. Front Cell Dev Biol. 2021 Mar 26;9:653579. DOI 10.3389/fcell.2021.653579.

Xu Q, Yu SB, Zheng N, et al. Head movement, an important contributor to human cerebrospinal fluid circulation. Scientific Reports, 2016; 19: 6: article 31787. Abstract: https://www.ncbi.nlm.nih.gov/pubmed/27538827

Zambrano M LA, Kilroy D, Kumar A, et al. The presence of Wormian bones increases the fracture resistance of equine cranial bone. PLoS One. 2021 Apr 16;16(4):e0249451. DOI: 10.1371/journal.pone.0249451.

Zhao J, Levy D. The sensory innervation of the calvarial periosteum is nociceptive and contributes to headache-like behavior. Pain. 2014 Jul;155(7):1392-1400. DOI 10.1016/j.pain.2014.04.019. Epub 2014 Apr 24.

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About the author

Dr Charles Masarsky has been in the private practice of chiropractic with Dr. Marion Todres-Masarsky since 1983. Their office is located in Vienna, Virginia, USA in the suburbs of Washington, DC. He also offers continuing education programs for chiropractic colleges and associations and teaches at George Mason University (Fairfax, Virginia). For information about his practice or his CE programs, please e-mail viennachiropractic@verizon.net.

Citations for Dr Masarsky's published papers are available at his website under '*about the doctors*': www.viennachiropractic.com.

Dr Masarsky writes this frequent feature in the *Journal* called '*The Wide Angle Lens*' in which he takes a broader than usual perspective on one issue or another, and has contributed much on clinical aspects of COVID.

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Masarsky CS, Todres-Masarsky M. Long COVID with Obstructive Sleep Apnea: A case report. Asia-Pac Chiropr J. 2025;6.1. www.apcj.net/papers-issue-6-1/#MasarskySleepApnea

Masarsky CS. Respiratory RCTs: What Are We Missing? [The wide-angle lens]. Asia-Pac Chiropr J. 2025;5.3. www.apcj.net/papers-issue-5-3/#MasarskyRespiratoryRCTs

Masarsky CS, Todres-Masarsky M. Long COVID with Parosmia and Exertional Malaise: A case report. Asia-Pac Chiropr J. 2025;5.4. www.apcj.net/papers-issue-5-4/#MasarskyLongCOVID

Masarsky CS, Todres-Masarsky M. Long Haul COVID-19 and Subluxation: A case report. Asia-Pac Chiropr J. 2022;2.6. apcj.net/papers-issue-2-6/#MasarskyLongCovid
.

Masarsky CS, Todres-Masarsky M. Long COVID Hyposmia/Parosmia and subluxation: A case report. Asia-Pac Chiropr J. 2022;3.2. apcj.net/Papers-Issue-3-2/#MasarskyHyposmia.

Masarsky CS, Todres-Masarsky M. Long COVID: A Risk Factor for Scoliosis Incidence and Exacerbation? [Hypothesis] Asia-Pac Chiropr J. 2023;3.3. apcj.net/Papers-Issue-3-3/#MasarskyLongCovidScoliosis.

Masarsky CS, Todres-Masarsky M. Long COVID Pharyngitis, Possible Glossopharyngeal Neuralgia, and Subluxation: A case report URL Asia-Pac Chiropr J. 2023;4.1. apcj.net/Papers-Issue-4-1#MasarskyTodreaMasarskyLongCovid

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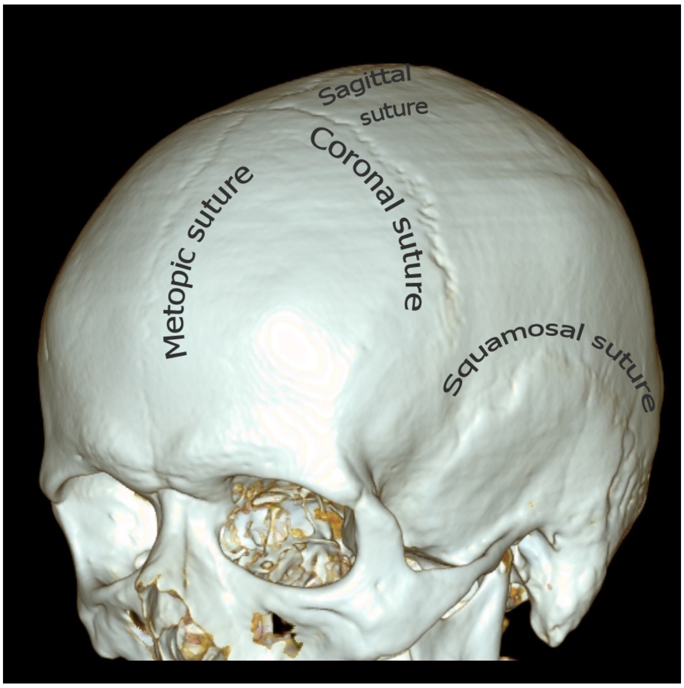
Image for context of metopic suture



Source: Persistent metopic suture - Radiology at St. Vincent's University Hospital at svuhradiology.ie