Early craniometric tools as a predecessor to neurosurgical stereotaxis

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In this paper the authors trace the history of early craniometry, referring to the technique of obtaining cranial measurements for the accurate correlation of external skull landmarks to specific brain regions. Largely drawing on methods from the newly emerging fields of physical anthropology and phrenology in the late 19th and early 20th centuries, basic mathematical concepts were combined with simplistic (yet at the time, innovative) mechanical tools, leading to the first known attempts at craniocerebral topography. It is important to acknowledge the pioneers of this pre-imaging epoch, who applied creativity and ingenuity to tackle the challenge of reproducibly and reliably accessing a specific target in the brain. In particular, with the emergence of Broca's theory of cortical localization, in vivo craniometric tools, and the introduction of 3D coordinate systems, several innovative devices were conceived that subsequently paved the way for modern-day stereotactic techniques. In this context, the authors present a comprehensive and systematic review of the most popular craniometric tools developed during this time period (prior to the stereotactic era) for the purposes of craniocerebral measurement and target localization.

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EARLY “craniometry,” referring to cranial measurements for the accurate correlation of external skull landmarks to specific brain regions, laid the groundwork for sophisticated advances in modern-day neurosurgical stereotactic techniques. Largely drawing on methods from the newly emerging fields of physical anthropology and phrenology in the late 19th and early 20th centuries, basic mathematical concepts were combined with simplistic (yet at the time, innovative) mechanical tools, leading to the first known attempts at craniocerebral topography. It is important to acknowledge the pioneers of this pre-imaging epoch and appreciate the creativity and ingenuity used to solve the challenge of reproducibly and reliably accessing a specific target in the brain. In this context, we present a comprehensive and systematic review of the most popular craniometric tools developed prior to the advent of modern-day stereotactic techniques for the purposes of craniocerebral measurement and target localization.

Early Anthropological Techniques

Physical anthropology aims to study the anatomical and physiological variations of the human body.²⁸ Anthropom-

etry, referring to the scientific collection and comparative correlation of measurements of the human body (including the major bones), evolved as one of the main techniques of this discipline.^{6,57} Originating in the 19th century, anthropometric measurements became popularized in a variety of contexts, ranging from subjective, controversial studies of racial typing to more systematic, biometrics-related applications for law enforcement.⁵⁹ In anatomical reference to external bone landmarks, it was found that simple measurements could be reliably made, including the cephalic index, i.e., the ratio of the breadth to length of the human skull.²⁷ Such early cranial-specific measures led to the related technique of craniometry, which has enabled modern-day anthropologists to characterize the progressive evolutionary changes in the shape and size of the human head as a function of an expanded brain volume.

Cranioscopy/Phrenology

Early methods were thus developed to empirically observe, examine, and describe the human skull, such that the shape and external anatomical landmarks of the cranium could be used to infer localization of brain function. This

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skull doctrine (or Schädellehre) was termed “cranoscopy,” and was popularized in the early 19th century by the German neuroanatomist and physiologist, Franz Joseph Gall (1758–1828).^{21,56} Cranioscopy, later known as phrenology, represented the earliest attempt at developing a methodology of functional localization and was generally met with great controversy at the time. To Gall, it was not sufficient to accept that mental ability resided in the brain; he argued that specific cognitive faculties were governed by dedicated regions (referred to as “organs”) within the brain. In 1 reported case, for example, Gall insisted that the findings of frontal lobe hypertrophy and exophthalmos were correlated with superior verbal memory tasks.²⁰ Although phrenology became fashionable in Gall’s time, it was largely discredited by scientific and religious communities in the middle of the 19th century. Nevertheless, certain components of the theory have endured to establish a foundation for modern neuroscience.⁷⁰

Broca and the Theory of Cortical Localization

Pierre Paul Broca (1824–1880), the famous French surgeon, anatomist, and anthropologist, further developed the field of cerebral localization. Among many other contributions to the neurosciences, he identified the role of the left inferior frontal gyrus in language articulation and conceived the notion of a dominant hemisphere (and its relation to handedness).^{3,7–9,61,69} In 1861, Broca first presented a now-famous case study of motor aphasia in a recently deceased patient with a lesion in the dominant (left) inferior frontal gyrus.¹⁰ In accordance with phrenological ideology, Broca took great interest in studying abnormalities of the skull, with careful observations of bone deformations, micro- and macrocephaly, and even the spectrum of craniosynostoses.^{48,55,61} However, it was Broca who definitively proved through his well-known case studies that function was localized to specific cortical regions and not just to external skull landmarks, thereby making the transition from Gall’s phrenology to the concepts underlying modern-day cortical localization theory.^{57,61} In 1880, for example, he presented a young, plagiocephalic, mathematical prodigy capable of rapid and accurate mental calculations to the Anthropological Society of Paris. This was yet another instance in which Broca attributed the patient’s advanced mental capacities to memory function (deemed the “psychological hypothesis”), rather than to his physiological differences and plagiocephalic skull morphology (i.e., the “phrenological hypothesis”), illustrating his early approach to the theory of cortical localization.⁴² In terms of other contributions, Broca prolifically developed more than three-dozen instruments, including specialized calipers and tools for measuring the interior of the skull (including a popular mandibular goniometer [Fig. 1]), and identified specific anatomical landmarks such as the glabella and theinion.^{5,6,12,59} He further compiled an extensive list of craniometric techniques, including an improved method for estimating the brain volume by measuring cranial capacity on the basis of quantified packing of the skull with gun shot or mercury, as opposed to water or fine mustard seed (Fig. 2); the advent of a primitive stereographic apparatus (the stereograph, discussed below); and the development of

FIG. 1. Illustration of Broca's mandibular goniometer. The apparatus, consisting of a base and the goniometer itself, was made of boxwood and copper. Mobile pins could be inserted into the external ear canals to secure the box against the head. The device could be used to measure the facial angle and the dimensions of the facial triangle, delineated by a line from the basion to the alveolar point, a line from the basion to the nasal point, and a line from the nasal point to the alveolar point. Reproduced from Broca P: Description d'un nouveau goniomètre. *Bull Soc Anthropol Paris* 5:943–946, 1864 (Public domain).^{5,6}

a widely accepted system for orienting the skull in reference to the alveolo-condylar plane, among other achievements.^{11,13,14,27,50,59} Interestingly, Broca even developed an in vivo methodology for localizing cerebral disease via thermoenkephalography, using a specialized (albeit rudimentary) crown of 6 to 8 symmetrically situated mercury thermometers capable of identifying a regional temperature difference across the head.^{15,17,55} In cases of compound depressed skull fractures, a difference of 1–3°C over an injured region was sufficient evidence to Broca to support surgical intervention using this method.⁶¹

Of particular interest, Broca's craniograph and stereograph were the preferred methods for postmortem drawings of skull anatomy by projection, and apparently required “scarcely any skill on the part of the operator.”⁶⁷ While the craniograph simply provided the outlines of the skull profile (including the location of the auditory meatus; Fig. 3), the stereograph provided additional details regarding all visible intricacies on the various surfaces of the skull. The latter tool consisted of placing a skull on a craniophore—an apparatus designed to hold the skull while measurements were directly taken—while the projection of a given surface of the skull was directly traced (Fig. 4A). Using the resultant image, the subsequent measurement of skull lines and curves was greatly facilitated, the latter's length typically measured using a “roulette millimétrique” (Fig. 4B) that itself was borrowed from sculptors who used it to measure the length of concave body surfaces.¹¹ Ultimately, Broca expanded from purely skull measurements to developing a methodology for measuring skull and brain relationships, by driving pegs through the skull to record the affected (underlying) brain convolutions in postmortem studies.^{30,61} In this way, he paved the way for the subsequent advent of surgical craniometry, focused on defining fixed coordinates along the cranium using ex-

FIG. 2. Hrdlička's device for measuring cranial capacity, as an expansion upon Broca's original invention. The skull was contained within a zinc vessel and placed atop a 2 L graduated glass tube. It was then filled with a measurable volume of a specific compound, in this case mustard seed (as compared with Broca's original design, who preferred gun shot or mercury). Release of the lever arm would open the funnel within the vessel, allowing flow of the compound agent into the graduated cylinder for subsequent measurement of the skull capacity. Reproduced from Hrdlička A: *Anthropometry*. Philadelphia: Wistar Institute of Anatomy and Biology, 1920 (Public domain).²⁷

ternal, measurable landmarks and linking these to the underlying cerebral topography.⁵⁷

In Vivo Craniometry for Cerebral Target Localization

In the late 19th and early 20th centuries, at a time when radiography was just emerging as the first imaging modality, various superficial topographic localization methods arose out of neuroanatomical cadaveric-based studies.⁶² A few particularly well-known examples are those of Taylor and Haughton's technique for identifying the central (ro-

FIG. 3. Schematic of a skull profile recorded using Broca's craniograph. The "O" reference point depicts the auricular point at the center of the auditory meatus, against which multiple other measurements could be made. Reproduced from Topinard P: *L'Anthropologie*. Paris: C. Reinwald et Cie, 1876 (Public domain).⁶⁷

landic) fissure,^{50,66} in addition to Keen's, Fraser's, and Kocher's access sites for puncture of the lateral ventricle.^{31,35} Additionally, several more elaborate skull craniographs were developed around this time, an example of which is shown in Fig. 5.⁶⁵ Moreover, a detailed description of additional puncture sites for exploratory brain aspiration was outlined in 1904 by Neisser and Pollack (using Kocher's craniometer, as discussed below); the latter also recognized the associated risk for injury to important arterial and venous vessels with these procedures (Fig. 6).^{31,41}

In parallel to these developments, attempts at functional localization were further advanced by the important introduction of electricity in experimental studies. Most notably, an experiment conducted in 1870 by Gustav Theodor Fritsch (1838–1927), an anatomist, anthropologist, and physiologist, and the neuropsychiatrist Julius Eduard Hitzig (1838–1907) showed evidence for excitable motor cortex in a dog, as a result of direct electrical stimulation to the brain itself.^{22,24} Sir David Ferrier (1843–1928), a Scottish neurologist-psychologist, conducted additional animal experimentation using electrical (Faradic) stimulation and lesioning in the brains of birds, cats, guinea pigs, dogs, rabbits, and macaques. His studies suggested that motor and sensory functions were consistently represented in an organized fashion within the cerebral cortex, furthering the modern-day understanding of the motor strip, a notion built upon the ideas of his mentor, John Hughlings Jackson, and those of Broca, among others.^{46,52}

It is in this context of newly recognized surface landmarks and an enhanced understanding of the location of the motor strip that the necessity was born for mechanical devices that would permit reliable, accurate, and reproducible measurements for in vivo target localization across

FIG. 4. **A:** Illustration of Broca's stereograph, depicting a skull seated on a craniophore as shown, which itself could be rotated depending on which view was desired. This device could systematically delineate skull outlines as projected tracings with measurable straight lines, angles, and curves, permitting accurate cranial measurements down to the millimeter. Reproduced from Topinard P: *L'Anthropologie*. Paris: C. Reinwald et Cie, 1876 (Public domain).⁶⁷ **B:** Traced curves were routinely measured through use of a roulette millimétrique, or graduated wheel. Reproduced from Broca P: *Sur l'endocrâne. Nouveaux instruments destinés à étudier la cavité crânienne sans ouvrir le crâne*. *Bull Soc Anthropol* Paris 8:352–383, 1873 (Public domain).¹¹

varying cranial shapes and dimensions. One such early device for readily locating the Rolandic fissure, Wilson's cyrtometer, consisted of a flexible, T-shaped metal scale secured around the cranium in coronal fashion, with an anteroposterior band extending from the glabella to theinion (Fig. 7).^{26,44} A third projecting strip was fixed at an angle of anywhere between 61° and 67°, and could be bent down directly to yield the course of the rolandic fissure.^{29,45} Similar cephalometers were developed by Krönlein and Köhler using measurements that were simple and easily remembered for the purposes of localizing the rolandic and sylvian fissures (and ultimately, the motor region).⁴⁹ Of note, Sir Victor Alexander Haden Horsley also reportedly developed a similar "Rolandic fissure meter."^{34,40}

In large part due to correspondence with Horsley, the Swiss surgeon Emil Theodor Kocher (1841–1917) developed a substantially improved craniometer consisting of 2 flexible, nickel-plated, steel bands with gradient markings

(in centimeters) situated around the equator of the head and along the sagittal plane from the glabella to the external occipital protuberance (Fig. 8).^{35,57} Kocher's device had screws to fix the bands in a rigid position, with a third band situated along the sagittal strip that could be adjusted to any angle, and with a fourth such strip that encircled the cranium in oblique fashion from the glabella to the lambda (to help identify the sylvian fissure). In comparison with its earlier predecessors, Kocher's craniometer could be easily applied to different head shapes and sizes in any age group, and was hailed by Harvey Cushing (among many others) as one of the best devices for craniocerebral localization of its time.^{18,31,36,57}

Emergence of 3D Coordinate Systems

Expanding on these early craniometric methodologies, a major advance in instrumentation for cranial localization in humans was the apparatus devised by the anatomist Dmitrii Zernov (1843–1917) and his pupil, Nikolai Altukhov, during the late 19th century in Russia.^{19,39} Zernov's primitive aluminum encephalometer comprised a horizontal ring secured at 5 sites to the patient's head, with a perpendicular band running along the coronal plane and with an adjustable meridian arclike device in the sagittal plane (Fig. 9).^{32,33,71–73} Spatial localization with this device was achieved using a spherical coordinate system (measured in degrees of longitude and latitude), and the system could also be used to determine the curvature of the skull.²⁵ Although the device never gained widespread use and was likely suitable only for superficially situated lesions, the apparatus appears to have been the first used clinically for localization and an important forerunner of today's stereotactic frame. Grigori Ivanovich Rossolimo (1860–1928), a Russian neurologist and one of the founders of pediatric neurology and psychiatry, subsequently developed a more refined system of measuring the surface of the head's 3D topography in 1907.^{25,51,53,54} Rossolimo modified Zernov's frame into a sphere-shaped helmet called the "cerebral topographer," which also included a soldered, hollow aluminum hemisphere (consisting of an engraved map of brain fissures, gyri, and subcortical structures), with small perforations interspaced along graduated parallels and meridians through which ink markings could be traced along the head surface (Fig. 10). This tool permitted the encephalometric marking of any cerebral structure to the overlying scalp, without restriction by the frame's arcs.^{25,32,33,54}

Ultimately, the mathematical use of spherical coordinates in these earlier devices gave way to implementation of the tricoordinate Cartesian system. As early as 1873, the physiologist Carl Dittmar (1844–1920) reported on a simplistic guiding device for his instruments, capable of producing consistent, circumscribed lesions in the rat medulla oblongata (specifically, within the bulbar vasomotor centers).^{1,43,47} Although some have offered that this device is the first historical sign of development leading to a stereotactic frame, it was not spatially coregistered in today's stereotactic sense.⁴

Arising out of subsequent elaborate studies of deep-brain structures in the cat and monkey, however, Sir Victor Alexander Haden Horsley (1857–1916; neurophysiologist

FIG. 5. Example of a craniometer and craniometric methods as developed by the Irish apothecary and craniologist, John Gratton (1800–1871). **A:** Drawing of an elaborate craniometer, permitting accurate outline tracings of the median (midline) section of the skull, but also transverse sectional outlines at any other desired point, by adjusting the vertical bar at position “E” in the diagram. **B:** Accurate measurements taken across various sagittal sectional outlines from a skull, showing the function of the craniometer device. Reproduced from Symington J: John Gratton’s craniometer and craniometric methods. *J Anat Physiol* 38:259–274, 1904 (Public domain).⁶³

FIG. 6. Neisser and Pollack’s proposed landmarks for exploratory brain puncture. The darkened black lines depict Kocher’s craniometer (further illustrated in Fig. 8), superimposed here for reference. Open circles reveal suggested points for aspiration in cases of suspected brain abscess, and the solid, black circles reveal suggested puncture sites for aspiration of the various lobes of the brain. Reproduced from Neisser E, Pollack K: Die Hirnpunktion. Probepunktion und Punktion des Gehirnes und seiner Häute durch den intakten Schädel. *Mitt Grenzgeb Med Chir* 13:807–896, 1904 (Public domain).⁴¹

FIG. 7. Schematic illustrating Wilson's cyrtometer, consisting of a scale for localizing the rolandic fissure. The device consisted of a flexible, T-shaped metallic band secured in the coronal plane, an anteroposterior band extending from the glabella to the inion, and a third strip (fixed at the shown angle of 67°) that could be bent over the cranium to reveal the course of the rolandic fissure. Reproduced from Park R: *Surgery of the brain, based on the principles of cerebral localization*. *Trans Cong Am Phys Surg* 1:285–328, 1889 (Public domain).⁴⁵

and neurosurgeon) and the mathematician Robert Henry Clarke (1850–1926) developed the first practical, Cartesian-based, stereotactic device that ultimately paved the way for modern stereotaxy.¹⁹ The term “stereotaxis” was originally derived by Horsley and Clarke, referring to the Greek stereos (meaning “solid”) and taxis (meaning “ordered” or “organized”).^{19,49} The Horsley-Clarke frame allowed for strategic direction of an electrode into cortical and subcortical structures, with guidance based on the Cartesian coordinate system. It eventually served as the basis for a modification by the Canadian neuroanatomist and neurophysiologist, Aubrey Mussen (1873–1975) in 1918, who developed it for human use.^{4,47} Eventually, however, Ernst A. Spiegel, Henry T. Wycis, Vernon Marks, and A.J. Lee presented their version of the Horsley-Clarke frame for use on humans in 1947, describing the first report of

FIG. 8. Illustration of Kocher's craniometer. Reproduced from Kocher T: *Text-book of Operative Surgery*. London: Adam and Charles Black, 1903 (Public domain).³⁵

FIG. 9. Zernov's encephalometer, one of the first known stereotactic devices for use in human patients, provided spatial localization on the basis of spherical coordinates. Reproduced from Kandel' ÉI, Shchavinskii YV: First stereotaxic apparatus created by Russian scientists in the 19th century. *Biomed Eng (NY)* 7:121–124, 1973.³² With kind permission from Springer Science and Business Media.

stereotactic operative techniques on the human brain. This definitively marked the starting point of the field of stereotactic neurosurgery.^{4,60} In close succession, further innovations were soon conceived by other eminent pioneers in the field of stereotaxy, including Jean Talairach, Jean Bancaud, Hirotaro Narabayashi, and Lars Leksell, among others.^{2,19,37,38,64,65,68} In this way, the modern era of frame-based and frameless stereotaxy was explosively propelled into the 21st century.^{16,23,58}

FIG. 10. Rossolimo's cerebral topographer, a spherical helmet modified from Zernov's original encephalometer, facilitated spherical coordinate measurements of cerebral structures to the overlying scalp. Reproduced from Kandel' ÉI, Shchavinskii YV: First stereotaxic apparatus created by Russian scientists in the 19th century. *Biomed Eng (NY)* 7:121–124, 1973.³² With kind permission from Springer Science and Business Media.

Conclusions

Early craniometric techniques stemming from physical anthropology and phrenology laid the groundwork for subsequent developments in craniocerebral localization techniques. The combination of basic mathematical concepts with simple (yet elegant) mechanical tools led to the first attempts at mapping the surface topography of the brain, and the challenge of consistently accessing a specific target on the brain's surface. Owing to the inventive and pioneering minds of the pre-imaging epoch, subsequent efforts at localization eventually led to the modern-day, 3D coordinate system-based methods that are now in widespread use. Given the tremendous changes observed in our discipline over the last 200 hundred years, it is exciting to anticipate what potentially lies in store for future patients undergoing stereotactic neurosurgical procedures.

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Author Contributions

Conception and design: both authors. Acquisition of data: both authors. Analysis and interpretation of data: Serletis. Drafting the article: Serletis. Critically revising the article: both authors. Reviewed submitted version of manuscript: both authors. Approved the final version of the manuscript on behalf of both authors: Serletis. Administrative/technical/material support: both authors.

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