Berengario’s drill: origin and inspiration

MICHAEL A. CHORNEY, B.S., CHIRAG D. GANDHI, M.D., AND CHARLES J. PRESTIGIACOMO, M.D.

Department of Neurological Surgery, Rutgers–New Jersey Medical School, Newark, New Jersey

Craniotomies are among the oldest neurosurgical procedures, as evidenced by early human skulls discovered with holes in the calvaria. Though devices change, the principles to safely transgress the skull are identical. Modern neurosurgeons regularly use electric power drills in the operating theater; however, nonelectric trephining instruments remain trusted by professionals in certain emergent settings in the rare instance that an electric drill is unavailable. Until the late Middle Ages, innovation in craniotomy instrumentation remained stunted without much documented redesign. Jacopo Berengario da Carpi’s (c. 1457–1530 CE) text Tractatus de Fractura Calvae sive Cranei depicts a drill previously unseen in a medical volume. Written in 1518 CE, the book was motivated by defeat over the course of Lorenzo II de’ Medici’s medical care. Berengario’s interchangeable bit with a compound brace (“vertibulum”), known today as the Hudson brace, symbolizes a pivotal device in neurosurgery and medical tool design. This drill permitted surgeons to stock multiple bits, perform the craniotomy faster, and decrease equipment costs during a period of increased incidence of cranial fractures, and thus the need for craniotomies, which was attributable to the introduction of gunpowder. The inspiration stemmed from a school of thought growing within a population of physicians trained as mathematicians, engineers, and astrologers prior to entering the medical profession. Berengario may have been the first to record the use of such a unique drill, but whether he invented this instrument or merely adapted its use for the craniotomy remains clouded.

Berengario and the Prince

As the son of a surgeon, Jacopo Berengario (c. 1457–1530 CE) was at birth set on a path to medicine. Born in 1457 CE in the city of Carpi, he was one of five children of the patriarch, Faustino Barigazzi.12 Trailing his father on house calls rooted Berengario’s interest in pursuing the medical profession, which culminated in a medical degree from the University of Bologna in August of 1489.12 Upon graduating at 32 years of age, the young Berengario returned home to Carpi and worked alongside his father to hone his medical skills.14

Despite an otherwise ideal father-son practice, Berengario would be forced to leave his father’s clinic in 1500 because of a verbal insult that Berengario directed toward the Duke of Ferrara, who had settled a dispute with Berengario’s patron.12 Determined to continue in medicine, he returned to Bologna and was appointed to the respected position of magister of surgery, and later of medicine, at the university in 1502.4 Berengario remained in Bologna until 1527.10

Drawing upon the masters who practiced centuries before him, Berengario succeeded in delivering an improvement to the trephine. He illustrated a compound brace and interchangeable bit tool resembling the modern-day Hudson brace, revolutionizing not only the craniotomy, but also the outlook of medical instrumentation.
Throughout his tenure at Bologna, Berengario was venerated with both acclaimed publications and esteemed patients. The Medici family of Florence, independently peerless in finance, networked with the emerging surgeon. Their paths first crossed by way of Pope Leo X (Giovanni di Lorenzo de’ Medici [c. 1475–1521 CE]), son of Lorenzo the Magnificent. The Pope appealed to the Bologna senate in 1513, which allowed Berengario passage to Florence to treat the Pope’s ailing relative without losing his position at the medical school. Graced with this commission, Berengario was consulted by the Medics for yet another family member and one of Berengario’s most influential patients.

Lorenzo II, Duke of Urbino (c. 1492–1519 CE), grandson to Lorenzo the Magnificent, suffered an occipital fracture in 1517, and among the entourage of physicians at his bedside appeared Berengario. Italy was in the midst of a power struggle between the papacy and surrounding states. Nepotism was common, and Pope Leo X strategically appointed his nephew, Lorenzo II, as duke of Urbino in 1516. Those loyal to Lorenzo II’s deposed predecessor blockaded the city of Mondolfo for nearly 3 weeks. In the battle for this city, Lorenzo II was injured by a harquebus, a substantial firearm similar to a musket.

Berengario believed the methods used to treat Lorenzo II, specifically the instruments, were inadequate and out of date. Lorenzo II represents the landmark patient, inspiring Berengario to write *Tractatus de Fractura Calvae sive Cranei*, published just 2 months after he returned to Bologna. The introduction of moveable printed type, present in Italy by the late 15th century, ensured that the text spread widely among the medical circles of Italy. The book is dedicated to Lorenzo II, a familiar honor for the Duke of Urbino, who was also the dedicatee of Niccolò Machiavelli’s *The Prince* in 1513.

**Medical Astrology: Prelude to Innovation**

Approaching the mid-13th century, medicine began a transition from speculation to specification. Before the age of randomized controlled trials, surgeons largely based their practice on clinical observations from a small population. Some practitioners compiled their observations into books for surgeons to learn and study. However, medicine lacked the clear clinical guidelines that modern surgeons use to make operative decisions.

As surgeons competed for wealthy patients and their referrals among society’s elite, they would presumably need to demonstrate the reasons behind their clinical decisions with excellent patient outcomes. Without randomized controlled studies, surgeons lacked large patient samples to refer to, but they could refer to the stars. Catarchic astrology, popularized in the Middle Ages, determined whether initiating an action or event at one point in time, based on planetary orbits, would promote success. These horoscopic castings, termed “elections,” were used for the foundation of large-scale cities, wars, and major medical operations. One notable example of this theory in practice relates to the Spanish astrologer and surgeon Abiathar Crescas (fl. 15th century CE), appointed to the royal court of King John II of Aragon (c. 1398–1479 CE) and who cast elections directing the treatment of the king’s cataracts in 1468.

Fifteenth-century physicians subscribing to this philosophy developed their treatment plans using elaborate tables designed on planetary orbits and calculated on computational instruments such as the astrolabe. Because of the ever-changing nature of the planets and the physicians’ need for accuracy, astrologers entered the field of medicine. These medical astrologers were at times, like Crescas, members of the royal courts and would accompany their patrons, along with the military engineers, during warfare. The creativity of the medical astrologers surrounded by war machines flourished, stimulating motivation to improve and redesign tools.

Medical astrologers served as an integral foundation for Renaissance physicians like Berengario. Conventional blacksmithe and engineers abundantly populated Europe, and their skills and education were imparted to their students through the apprentice system. As such, textbook learning infrequently entered the classroom for these students of applied metallurgy, and thus few books on their trade surface during this period. Medical astrologers were educated as physicians, using textbooks, and their mentality incorporated the need to transmit their knowledge through writing. They rebuked medical tools as being too crude for the precision required to operate and set out to redesign and fabricate exacting instruments.

The popularity of medical astrology waned toward the end of the 15th century, however, and the trend in medicine toward the scientific model was underway. Astrologers introduced newer, modern instruments, like the astrolabe, to the medical field. Physicians like Berengario would begin to critically assess the design of tools inherited from their predecessors and explore novel means of operating. The trephining drill represented one target due for innovation.

**The Trephine**

Few tools in surgery operate more gracefully than the trephine. Simple in design, the trephine is used by neurosurgeons in some of the most critical procedures. The trephine throughout its history has been intermittently modified. Concerns about craniotomies may have precluded surgeons from wielding the device, but no argument protests the tool’s ability to complete the task of opening the skull.

Hippocrates (c. 460–370 BCE) depicts the crown trephine (“modiolus”) around the year 300 BCE (Fig. 1). His explanation of the tool’s use echoes to this day: provide torque, via a throng or cross handle, with the saw blade perpendicular to the calvaria. The crown trephine sports a serrated saw curled cylindrically on the flat plane. Upon alternating pronation and supination, an annular groove is cut into the bone, facilitating the removal of a cylindrical portion. Skulls retrieved from the fossil record show singular holes or multiple communicated holes to achieve a craniectomy. Regardless of the objective for each hole burred, Hippocrates acknowledges the utility of an array of caliber trephines, accommodating
skulls of various ages and injuries. The major hindrance to a surgeon’s confidence in the modiolus centered on the capacity to easily penetrate the skull.

The next major improvement to the crown trephine was a removable center pin first described by Aulo Cornelio Celsus (c. 25–50 BCE) around 30 BCE. The function of the pin was to steady the saw blade against the skull to accurately position the hole. Some trephines developed later would affix this center pin permanently, facilitating the use of both male and female derivations. Once the male trephine began to cut into the bone, the female trephine continued burring. Celsus also asserted that correct pressure on the trephine would result in both burring and rotation—too much pressure and the tool would cease, too little and the tool would not advance.

The crown trephine, actively used through the time of Galen (c. 129–199 CE) into the Middle Ages, fell out of favor and was replaced by the “torcular” (Fig. 2). The torcular, Latin for a wine or oil press, stood as a three-legged instrument (sometimes two) placed around the skull. This device used a gimlet, which elevated bone fragments after penetrating the center of a cranial depression. The gimlet ended in a screw point and progressively extended to helical flutes with a curved edge producing a shearing force against the surface. For added control, gimlets were attached to a collar (“abaptista”) to prevent unwanted intrusion through the meninges. The distance between collar and screw point was fixed and required the surgeon to stock a variety of the mounted torculars to penetrate various skulls.

The crown trephine would re-emerge during the late Middle Ages. Leonardo Buffi da Bertipaglia (fl. 15th century), a surgeon trained at Padua, reintroduced the circular trephine in the 15th century. The revived tool would soon become the focus of Berengario’s signature publication and undergo a redesign that would ensure the tool’s survival for centuries.

Berengario’s Drill

War creates unexpected trauma to which surgeons must adapt their skills to best aid injured soldiers. Renaissance Italy, despite its beautiful art and architecture, was immersed in conflict among powerful families vying for influence and power. Surgeons to these families and armies were faced with an increase in skull fractures and trauma, which were attributable to the broad use of gunpowder. The need for craniotomy increased accordingly. However, standard care in the Middle Ages discouraged the use of craniotomy, based on the belief that air had a harmful effect on exposed brain, and instead favored the medical management of brain injuries.

The boom in craniotomies with the advent of ballistic warfare can be explained by a number of factors. Exact figures are difficult to ascertain, but a widespread increase in skull injuries supposes a prompt need for treatment. In addition, just the fact that a patient’s brain was exposed to air from the impact, in some cases, may have justified the craniotomy to Middle Ages–trained surgeons in the Renaissance.

Assuming these injuries were rampant in battle, new tools would have to be developed to increase the speed and efficacy of the craniotomy. The resolution to this challenge epitomizes Berengario’s primary contribution to the history of the procedure. Tractatus de Fractura Calvae sive Cranei circulated among academe starting in 1518, the year after Berengario consulted at the bedside of Lorenzo II. Despite Berengario’s belief in a treatment plan different from the
one used, Lorenzo II healed within a month.\textsuperscript{14} Berengario departed Mondolfo believing that the care provided to Lorenzo II, as well as the instruments, did not qualify as up-to-date medical care.\textsuperscript{14} The disgruntled professor returned to Bologna to vent his frustrations on paper.

Berengario devotes his text largely to codifying the array of skull injuries as well as their surgical and medical management. While many of his remedies have largely fallen out of the modern physician’s apothecary—for example, plasters made from cow’s milk—his design of the braced crown trephine survives.

Surgical tools aside, Berengario advocated for a conservative approach to surgery. He believed that the decision to operate on a patient commanded the utmost reverence. Berengario acknowledged the severity of surgery and wrote extensively in \textit{De Fractura} on the danger of an under-skilled surgeon wielding instruments. He stated, “for such a task a man of intellect and familiarity with such operations should be found, one who by nature and complexion is skillful in the art and has practiced it for a long time, since he must not be accepted unless he has served as a disciple of a most perfect master in surgery and has himself practiced it for a long time.”\textsuperscript{12}

Perhaps the strongest support for Berengario’s conservative use of surgery resides in the organization of his text. Three chapters of the 19-chapter volume concentrate on the surgical technique for and management of head wounds; these chapters are also the last in his book. The most important skill a physician can foster, above surgical technique, is judgment, and Berengario elegantly writes, “I pray to the highest God that he direct me to an accurate prognostication because nothing is tougher, harder, scarcer, and more difficult in medicine than to deliver a correct judgment.”\textsuperscript{12}

In perusing the Latin text, the viewer encounters Berengario’s illustrations of the tools he describes. Effectively, the only illustrations appearing in this text feature the instruments used in the craniotomy. One theory to explain the scarcity of illustrations may relate to the speed with which Berengario wanted to publish his work. To hire an illustrator to draft detailed scenes and specimens required ample time and resources. Perhaps Berengario desired to be the first among Lorenzo II’s physicians to dedicate a text in his honor. Quite possibly, the depictions of the tools represented blueprints rather than illustrations. Large medical suppliers were scarce in the 1500s, and local blacksmiths served as apt manufacturers of iron-based medical equipment. The images supplied in the text are very clear, presumably to aid in re-creation. Even if a physician or blacksmith did not read Latin, the principal language of the text, the designs could still be understood.

The one tool this volume fixes upon is what Berengario describes as the “vertibulum.” This device single-handedly expresses Berengario’s greatest contribution to the craniotomy. The vertibulum was a revolutionary tool, having two features first defined in a medical text: the compound brace and the interchangeable drill bit.

The brace itself had three components (Figs. 3 and 4). Atop the tool rested a bidirectional, rotatable sphere to be held in the operator’s nondominant hand, as indicated by Berengario, or placed with direct pressure via the chest, chin, or forehead.\textsuperscript{1} The middle portion was cylindrical, for enhanced movement with the dominant hand, and the bottom contained the head, where the bits were placed.

Contemporary use of the Hudson brace, which is similar to Berengario’s brace, dictates the use of both a perforator and a bur bit. The perforator initially creates a small opening through the cranium, while the bur expands the window.

The design of the brace is purposeful. Mechanically, the device can be operated at varying speeds with different effects. At low speeds, the bit removes a large portion of material per revolution and requires greater torque.\textsuperscript{9} This would have been the preferred modus operandi for surgeons, offering more control. However, at high speeds the tool works to the contrary. Berengario did not discuss the speed at which the drill must be turned, but it can be surmised by his forewarnings that the over-expeditious surgeon encounters complications: “one of my colleagues, anxious to operate, began first with a certain instrument of middle size and then changed to a straight slender one.
The instrument finally entered violently under your [Lorenzo II’s] cranium from which experience you escaped unharmed although you were in some danger.”12

The biggest concern Berengario discusses regarding the procedure is the penetration of the meninges. But the brace may not have reduced that risk, according to sources.1 Despite increasing the speed and reducing physical strain of the operator, more downward force may presum-ably have been placed on the brace. On the contrary, the crown trephine requires much more work on behalf of the operator, utilizing the shoulder and forearm muscles.1 This reduction in physical strain may have enhanced the operator’s perception while using the brace and possibly reduced unwarranted breaching into the meninges.

The introduction of the interchangeable trephining bit by Berengario served a clear purpose: to reduce device costs to physicians. Multiple bits of various shapes and sizes were not a novel idea. As previously stated, physicians stocked multiple crown trephines depending on the bone topography and thickness. Likewise, Berengario describes bits shaped differently from just the tapered shell bit, and thus with one brace, the cost of acquiring more bits was reduced. Perhaps an even subtler reason for the interchangeable bit is the idea that Berengario recognized the need for surgeons to be able to create new bits if the job required it:

“A case will come into the physician’s hands which he has never seen before and he will prepare a new instrument for this case. This has happened to me many times. I immediately caused to be prepared and even made with my own hands new instruments designed for that particular fracture which I never used thereafter nor saw before. Therefore there may be a great number of tools of every kind: very small, small, middle-sized, large, and larger. Beyond everything the physician should be ingenious and of good judgment because then he will not lack instruments. Legitimate physicians, however, have or ought to have cabinets full of such instruments.”12

Given the size of the brace, coupled with the assumed high cost of manufacture, the most effective way for a surgeon to travel and carry the other tools they required was to separate the bit from the brace.

Among the array of bits Berengario detailed, one remained principal, the “terebrum canulatum” (Fig. 3). The canulatum resembled the crown trephine, with a central pin, or “aculeus,” that Berengario would have been familar with after its reintroduction by Bertapaglia, whom he cites in De Fractura.12 One look at Berengario’s illustration of this bit will immediately strike the viewer as progressive. The bit itself is flanked by two strategically placed projections, or “alae.” These thin wings provide both a cutting action expanding the bur and a protection mechanism, as the broad portion impedes further penetration. His last remark on the canulatum, compared with the eight other bits Berengario displays, is full of praise: “This instrument in my judgment exceeds all others if it is handled by an expert and diligent physician.”12

The Origin of the Brace

The brace exemplifies a simple yet elegant standard of mechanics: the ability to convert reciprocating to rotary motion. This advancement in tools, most likely rooted in ancient Egypt, is considered by some to be second only to the wheel in importance.20 In addition, the introduction of Berengario’s brace epitomizes the antecedent of modern medical tools.6 However, rummaging through an old collection of tools at a yard sale uncovers a carpentry tool so strikingly similar to Berengario’s that its origin warrants investigation.

Berengario supplies the readers of De Fractura with information about notable physicians, including Galen, Avicenna, and, heavily, Celsus. But Hippocrates is cited only to the extent that Galen references him. Berengario does not even consult Hippocrates’ On Injuries of the Head, which Lind describes as “exclusively devoted to skull fractures.”12 However, with respect to the brace, Berengario is as unlikely to reveal his inspiration as he is to praise the physicians caring for Lorenzo II.

As previously mentioned, the origin of the brace rests in antiquity, which after centuries of derivative innova-
tions led to the modern carpenter’s brace. From what has been written on the history of the brace, Berengario may have been inspired to develop this tool based on the direct scholarship of his predecessors in medical astrology or an encounter with the carpenter’s brace in Italy.

The carpenter’s brace was invented by Flemish artisans around 1420 CE in what is now northern Belgium. Representations of the carpenter’s brace can be found in other locations of northern Europe. Nevertheless, carpenters were burring holes with the tool almost a century before Berengario wrote his text. The first suggestion of such a tool existing in Italy appears as a sketch by Italian physician Giovanni da Fontana (c. 1395–1455 CE).

Fontana was a Venetian craftsman and inventor before attending medical school at Padua in 1421. As a respected clinician, he continued to study mechanics and was a productive writer. In a collection of sketches published in the 1430s under the title Bellicorum instrumentorum liber (Book of War Instruments), Fontana depicts many fantastic instruments of war. Buried within the book is an illustration of a brace with a fixed screw-point auger bit (Fig. 5). Historians state that Fontana’s design indicates that he may have heard of such a device only in passing, and argument exists over whether Fontana’s brace mechanically functioned as intended. Nonetheless, functioning versions of the compound brace spread through Italian circles. Europe was engulfed in the advancement the compound brace brought across various industries of construction.

Berengario would have presumably been exposed, perhaps indirectly, to the works of medical astrologers and engineers during his training at Bologna. While the direct inspiration for his drill remains unknown, we can speculate that a young Berengario looked upon the pages of books like Bellicorum instrumentorum liber and allowed his mind to wander through the pages of mechanical designs synthesized by physicians. Conceivably, he unearthed a crank and connected the rotary motion of the crank to that of the crown trephine. Quite possibly as well, Berengario, while traveling through Renaissance Italy amid the grandiose architectural construction, witnessed a carpenter drilling effortlessly with a compound brace, thinking that a surgeon could do the same with bone. While Berengario affirms “the physician is not a carpenter,” the physician may very well have been inspired by the carpenter in this regard.

An alternative hypothesis to the acute appearance of the compound brace in Berengario’s text rests in the exclusivity of medical devices. As previously described, Italy divided itself into states ruled by powerful families. These city-states fought not only for land but also for intellect. Presumably, the uniqueness of the compound brace, coupled with the lack of patents protecting the design, would have compelled its absence from medical texts. The brace Berengario describes could have been in use for decades by surgeons in Bologna, and Berengario unknowingly documented the drill on paper without knowing its origin.

Conclusions

Tractatus de Fractura Calvae sive Crani was certainly one of the most influential volumes defining neurosurgical craniotomy techniques for centuries. While not a complete treatise on surgery, the text serves as an integral part in the history of surgery. Supporting its significance is Berengario’s drill, a compound brace. The compound brace represents a significant advancement in modern engineering. Its use spread rapidly through medical circles and was extensively detailed by Giovanni della Croce’s 1573 text on surgery.

Berengario’s drill is the first compound brace recorded in a medical text. History veils the direct source of Berengario’s inspiration for such a device. However, the trend in medicine of shifting away from the humanities and into the sciences cultivated the mindset for physicians to question their tools and methods. Students of medicine were entering training with backgrounds in mathematics and engineering, and these men were eager to expand their toolbox to practice a more sophisticated, exact medicine.

The rise in craniotomies was directly connected to the use of gunpowder in warfare. Given the potential danger of penetrating the meninges, craniotomies would have to be made more efficient without compromise to safety. Berengario’s drill served such a need with regard to burring the hole. The interchangeable bit and brace design allowed surgeons to carry more trephining instruments, decreased manufacturer costs, and opened the possibility for experimental bits to be designed with little expense. The canulatum Berengario describes utilizes wings to reduce meningeal penetration, thus curtail the overexpedient surgeon who may have had multiple craniotomies to complete.

Without question, the drill Berengario introduced to the field of medicine revolutionized the craniotomy, al-

![Fig. 5. Sketch of the compound brace by Fontana (c. 1430s). Fontana's brace is the earliest documented compound brace in Italy. The brace is described in the context of construction. Critics argue that Fontana, both a physician and an inventor, had little mechanical experience with such an instrument. His depiction of the brace would lead one to think that it does not appear to function as intended. Image courtesy of the Bavarian State Library, Munich: Bayerische Staatsbibliothek München Cod.icon. 242, fol. 40v.](image-url)
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though it was possibly not an original design. Documentation of the drill during a period of widespread printing of texts ensured broad dissemination among practicing surgeons in Italy. At minimum, Berengario’s drill is inferred from centuries of experiments in mechanical design. Nonetheless, modern versions of Berengario’s drill are still available on the market today. The simplicity of the drill, in both motion and design, remains a timeless instrument that has served the field for centuries.

In his text Berengario describes other tools necessary to complete the craniotomy. Focusing extensively on identifying various skull fractures and the medical and surgical management of patients, Berengario buries his drill, almost minimizing its significance to the modern viewer. However, images communicate to modern neurosurgeons not trained in Latin. A simple perusal of骨折 De Fractura instantly allows the neurosurgeon to recognize the instrument that has served the field for centuries.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

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