of intracranial pressure following cranioplasty; while, implantable Doppler devices, which continuously monitor blood flow following free flap placement, have seen success in early clinical trials, preemptively identifying clotting and abating the need for rescue interventions.[6,7] In addition to paradigmatic changes in patient care, IoT innovations like those aforementioned, have been foundational in the formation of burgeoning craniofacial adjacent subspecialties notably—neuroplastic surgery.[8,9]

However, to achieve the full potential of this nascent technology, both for patients and the field, involvement of clinical experts throughout the development process is crucial (Fig. 1 highlights various roles clinicians may play). Auspiciously, although development efforts have classically been considered prohibitively costly and complex, the advent of affordable computing and sensing technologies, such as Raspberry Pi and Arduino have radically simplified the prototyping process; now achievable without technical training, in a few hours, for barely more than the cost of materials.[10,11] However, the translation of these devices is not without challenges, cybersecurity being chief among them, and device developers must take a proactive role in ensuring security and safety.[12]

In summary, although IoT devices continue to gain public notoriety, these tools represent a largely unexplored frontier in craniofacial surgery. To implement these devices, clinician involvement is crucial throughout the development process from ideation to implementation. We present a simple framework for smart device ideation and hope that when faced with clinical challenges, craniofacial surgeons consider these potentially paradigm-shifting IoT tools.

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REFERENCES

1. Sadoughi F, Behmanesh A, Sayfouri N. Internet of things in medicine: a systematic mapping study. *J Biomed Inform* 2020;103:103383
2. Lou D, Pang Q, Pei X, et al. Flexible wound healing system for pro-regeneration, temperature monitoring and infection early warning. *Biosens Bioelectron* 2020;162:112275
3. Niesche A, Müller M, Ehreiser F, et al. Smart bioimpedance-controlled craniotomy: concept and first experiments. *Proc Inst Mech Eng H* 2017;231:673–680
4. Turer DM, Qaium EB, Lawrence AM, et al. A smart sensing cannula for fat grafting. *Plast Reconstr Surg* 2019;144:385–388
5. Hatefi S, Etemadi Sh M, Yihun Y, et al. Continuous distraction osteogenesis device with MAAC controller for mandibular reconstruction applications. *Biomed Eng Online* 2019;18:43
6. Kim SH, Shin HS, Lee SH. "Internet of Things" real-time free flap monitoring. *J Craniofac Surg* 2018;29:e22–e25
7. Mitchell KS, Anderson W, Shay T, et al. First-in-human experience with integration of wireless intracranial pressure monitoring device within a customized cranial implant. *Oper Neurosurg (Hagerstown)* 2020;19:341–350
8. Mitchell KS, Shay T, Huang J, et al. The neuroplastic surgery fellowship experience: where tradition meets innovation. *J Craniofac Surg* 2021;32:12–14
9. Gordon CR. The special field of neuroplastic surgery. *J Craniofac Surg* 2021;32:3–7
10. Raspberry Pi Foundation. Teach, learn, and make with Raspberry Pi. 2022. Available at: https://www.raspberrypi.org/ Accessed January 27, 2022
11. Osman Z, Ahmad A, Muharam A. Rapid prototyping of neonatal jaundice detector using skin optics theory. *IEEE Conference on Biomedical Engineering Sciences*; Vol: 328–331. 2014
12. Malhotra P, Singh Y, Anand P, et al. Internet of things: evolution, concerns and security challenges. *Sensors* 2021;21:1809

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Discussion on: "Let's Smarten Up: Smart Devices and the Internet of Things, an Untapped Resource for Innovation in Craniofacial Surgery"

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Abstract: Prior to Dr. Paul Tessier's teachings in the 1960's, many neurosurgeons and craniofacial surgeons took shortcuts and employed alloplastic materials fraught with complication, and soon thereafter, both surgical specialties moved the pendulum towards the side of bone grafts being the gold standard for neurosurgical reconstruction and the art of cranioplasty. But now half a century later, neuroplastic surgery is moving the pendulum the other way. Without a doubt, the brain is a critical organ that needs some form of modulation as opposed to replacement. The intervention delivered can be in the form of electricity, light, medicine, etc. Regardless of the medium, it needs to be housed somewhere. And there is no better real estate than to be housed within a sterile alloplastic case with embedded smart technologies; in a way that prevents obvious,

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visual deformity. For example, it would be naïve to think that the future of embedded neurotechnologies will one day be housed safely and dependably within one's own bone flap. Hence, moving forward, time-tested alloplastic materials will become the new gold standard for cranioplasty reconstruction as the world starts to welcome a generation of smart cranial devices; some of which may house Bluetooth-connected, Wifi-enabled, MRI-compatible pumps to perform convection-enhanced delivery of time-tested medicines – thereby forever changing the way we approach chronic neurological disease and the forever-obstructing, blood-brain barrier. As this happens, I feel confident saying that both Tessier and Cushing are somewhere applauding and smiling on these efforts.

Key Words: smart, technology, craniofacial, cranioplasty, skull, cranial, implant, device

In 1967, Dr Paul Tessier, the father of modern-day craniofacial surgery, performed his first set of pediatric operations, thereby forever establishing a new frontier known as craniofacial surgery. On a mission to break endless boundaries alongside his neurosurgical colleagues, he spent the latter half of the 20th century inventing numerous methods for using one's own bone (ie, bone grafts) as opposed to using foreign, nonautologous segments of alloplastic materials (eg, silicone, acrylic) to successfully create masterful results in the setting of complex face/skull reconstruction for severe deformities.[1] To use a plastic implant as opposed to bone would in recent times be seen as "criminal" and "unjustified" by anyone following the thought processes of our legendary figure, Dr Tessier. This breakthrough in concepts was exactly what the field of craniofacial plastic surgery needed, especially since the infection rate back then for foreign materials in skull/facial reconstruction cases was astronomical, and 3D printed technologies with computer-aid design/computer-aided manufacturing had not been fully developed.

There seems to be some evidence that the pendulum is swinging back the other way. For instance, on Monday, September 16, 2019, I had the great privilege and honor of opening the International Craniofacial Surgery meeting in Paris, France, with a lecture entitled "Introduction to multidisciplinary panel and burgeoning field of neuroplastic surgery." The lecture kicked off an 80-minute panel summary of many neuroplastic surgery strategies, approaches, techniques, and newly designed functional cranial implants to replace cranial bone and further optimize newly created neurotechnologies for achieving safe brain modulation, improved brain function, and/or enhanced brain neuroimaging/diagnostics, while at the same time providing the patient an optimal reconstruction and absent deformity.[2–5] Of course, this was all thanks to the kind invitation received by the event chairman, Professor Eric Arnaud.[6] But to say it was unanimously well received would be an inaccurate report by any stretch of the imagination. The majority of the 800-member audience—complete with mostly pediatric craniofacial surgeons and pediatric neurosurgeons—were shocked and dismayed by the presentations put forth that normal bone could at some point be considered something other than the "gold standard." In fact, the responses were quite similar to what I would have expected to receive at the very first international craniofacial meeting held in Cannes, France, in September 1983 with Dr Tessier present in the audience. Passionate statements such as "Why would you ever replace someone's healthy bone with a foreign, non-autologous portion of synthetic plastic?" were common and heard quite clear. Interestingly, however, I would also imagine this was the same negative feedback Dr Tessier received in the mid-20th century during his trailblazing presentations and prior to transitioning his reputation from "cowboy" to "pioneer."

Now fast forward three years, I am quite proud and humbled to see the article published here by Brydges et al[7] from NYU Langone Health entitled "Let's smarten up: smart devices and the internet of things, an untapped resource for innovation in craniofacial surgery" in this month's issue of *Journal of Craniofacial Surgery*. During the group's review of the literature, the authors reveal a multitude of highlighted areas for which have helped best demonstrate the recent entrance of "smart" technology into the arena of craniofacial surgery. For instance, they span from temperature sensing smart bandages to real-time navigated tools to smart cannulas for fat grafting to smart distraction devices to the likes of wireless, smart implantable Doppler's. Brydges and colleagues go even further to enlighten us with the creation and inclusion of a high-yield schematic figure demonstrating the multiple stages of "Clinician-driven Development" as it relates to smart use technologies. Ironically, one should also take a second to realize that none of these summarized technologies were around during Dr Tessier's career. Each of them, however, now resembles a potential promise to enhance patient outcomes and thereby help extend the boundaries of modern-day medicine.

In 2021, I had the great fortune of publishing an invited editorial in honor of Dr Harvey Cushing entitled "The special field of neuroplastic surgery" in this prestigious journal.[8] Of note, the title was purposeful in that it mirrored the one chosen by Cushing as the pioneer and father of modern-day neurosurgery, "The special field of neurological surgery," as he wrote to his colleagues at The Johns Hopkins Hospital Bulletin back in 1905, introducing this new field. Notably, he stayed on course even though Dr William Halsted, his Chief, thought that a career focused solely on brain surgery was nothing but a wasteful, lackluster endeavor.[9] With this article, I spoke to the *Journal of Craniofacial Surgery* audience about how times were quickly evolving, and that at some point, we must force ourselves to breakthrough the dogma set before us over a half a century ago. We should no longer envision that bone grafts will forever represent the gold standard as put forth by Dr Paul Tessier and all subsequent trainees. Of course, this was in no way meant to be disrespectful to Dr Tessier and/or to criticize the safer choice in some instances. Instead, it is meant to provide an eye-opening invitation to everyone to work together and to open the mind's potential to technology advancements, which hold great promise for humankind and our neuroplastic/neurosurgical patients, especially for who come to us desiring state-of-the-art cranioplasty reconstruction. Unquestionably, chronic brain disease is one of the most challenging, expensive, and daunting burdens facing our nation's healthcare system today. Ask yourself what would be more satisfying for us as a field to collaborate, design, invent, and engineer as the next century of "smart cranial devices" with the likes of young, inspired craniofacial plastic surgeons early on in their career trajectory?

Remember, neurosurgeons are the undeniable experts of the brain and central nervous system. At the same time, we are the experts of the skull, scalp and face—or the "extradural surgeon" to be more precise—coined to me by our editor-in-chief, Dr Mutaz Habal. As plastic surgeons, we are known collectively as the "ultimate problem solvers." Thus, we should transition away from the be-all and end-all mentality that bone grafts are the everlasting gold standard and realize that the future of embedded neurotechnologies will never be encapsulated within one's own bone graft/flap. Instead, these lifesaving/life-changing

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"smart" modalities will be surrounded by safe, time-tested alloplastic materials, 3D printed and assembled in sterile fashion.[2–4] Also, within will be a culmination of technologies that have only developed in recent times. In simpler terms, Dr Tessier did not have a cellphone to use while making rounds, so he could not employ a smart phone app to visualize and test the flow within an implantable Doppler monitoring one of his scalp free flap-cranial reconstruction patients. In fact, one would think his astute prowess for enhanced outcomes and patient safety would have made him a great champion of futuristic, wireless free flap monitoring. In parallel, Dr Cushing did not have a Wi-Fi-enabled or Bluetooth-connected device to connect to his brain tumor patient's novel cranial device, wishing to have some chemotherapy medicine delivered directly to the brain to bypass the blood-brain barrier, eloquently in line with the concepts and science first described by Dr Oldfield at the National Institutes of Health in the early 1980's.[10] Like Tessier, Dr Cushing was a profound scientist constantly pushing the boundaries of science; therefore, he would have undoubtedly welcomed this type of smart technology into his practice with open arms.

To this point, I congratulate our colleagues at NYU for publishing their timely article and providing the *Journal* audience with their summary of the latest and greatest smart technologies being developed for craniofacial surgeons caring for face/scalp/skull deformities. The "Internet of Things" concept stands to enhance patient safety and surgeon operability by sensing, predicting and alerting to a myriad of variables that were previously reactionary in patient care. It also highlights the importance of clinician involvement in technological innovation. Thus, in the spirit of Dr Tessier and Dr Cushing, we should always remember to push through boundaries set forth to us by previous surgical generations and remind ourselves that newer technologies are just around the corner waiting for us to embrace them, develop them, further innovate, and then successfully and responsibly integrate them within our very own craniofacial practice, exactly as one learns to drive their Tesla and forcibly ignore the local gas station going to and from work each day. Stop for a second and consider the fact that there were no electric vehicles for Cushing or Tessier to drive, but no doubt they could and would find a way to accept this form of innovation. As such, we as a specialty can do the same. We can and should recognize that the pendulum is now swinging back the other direction. There are many high-level papers demonstrating statistical evidence that FDA-approved, alloplastic implants placed correctly and in sound fashion will accompany a lower rate of complications, including infection and/or the need for revision surgery.[11]

Prior to Tessier's teachings, many surgeons took shortcuts and employed alloplastic materials fraught with complication, and soon thereafter, craniofacial surgery moved the pendulum towards the side of bone grafts being the gold standard for neurosurgery and the art of cranioplasty. But now half a century later, neuroplastic surgery is moving the pendulum the other way. Without a doubt, the brain is a critical organ that needs some form of modulation as opposed to replacement. The intervention delivered can be in the form of electricity, light, medicine, etc. Regardless of the medium, it needs to be housed somewhere. And there is no better real estate than to be housed within a sterile alloplastic case. For example, it would be naïve to think that the future of embedded neurotechnologies will one day be housed safely and dependably within one's own bone flap. Hence, moving forward, time-tested alloplastic materials will become the new gold standard for cranioplasty reconstruction as the world starts to welcome a generation of smart cranial devices. As this happens, I feel confident saying that both Tessier and Cushing are somewhere applauding and smiling on these efforts.

REFERENCES

1. David D. Obituary—Dr. Paul Tessier. *JPRAS* 2008;61:1008
2. Gordon CR, Santiago G, Liu J, et al. First in-human experience with complete integration of neuromodulation device within a customized cranial implant. *Oper Neurosurg* 2018;15:39–45
3. Gordon CR, Wolff A, Santiago G, et al First in-human experience with integration of a hydrocephalus shunt device within a customized cranial implant. Oper *Neurosurg (Hagerstown)* 2019;17:608–615
4. Mitchell KA, Anderson WA, Shay T, et al. First in-human experience with integration of wireless intracranial pressure monitoring device within a customized cranial implant. *Oper Neurosurg* 2020;19:341–350
5. Belzberg M, Ben-Shalom N, Yuhanna E, et al. Sonolucent cranial implants: cadaveric study and clinical findings supporting diagnostic and therapeutic trans-cranioplasty ultrasound. *J Craniofac Surg* 2019;30:1456–1461
6. ISCFS 2019 Program. Available at: https://www.iscfs.org/wp-content/uploads/2020/01/ISCFS19_prgfinal_20190902.pdf
7. Brydges BS, Boczar D, Trilles V, et al. Let's smarten up: smart devices and the internet of things, an untapped resource for innovation in craniofacial surgery. *J Craniofac Surg* 2022
8. Gordon CR. The special field of neuroplastic surgery. *J Craniofac Surg* 2021;32:3–7
9. Cushing H. The special field of neurological surgery. Bulletin of the Johns Hopkins. *Hospital* 1905;16:77–87
10. Lonser RR, Sarntinoranont M, Morrison PF, et al. Convection-enhanced delivery to the central nervous system. *J Neurosurg* 2015;122:697–706
11. Belzberg M, Ben-Shalom N, Mitchell KA, et al. Cranioplasty outcomes from 500 consecutive neuroplastic surgery patients. *J Craniofac Surg* 2022;33:1648–1654

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