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Breaking boundaries in neurosurgery through art and technology: A historical perspective

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ABSTRACT

Introduction: Since the past, art has been used as a tool to elaborate anatomical knowledge and guide surgeons to perform surgeries. Through the eras, art has taken role by conveying the knowledge to people in forms of illustrations and models, including neuroanatomy knowledge for neurosurgical purposes. With the advancement of technology, neurosurgical trainings and care evolve more than before.
Research question: How do art and technology play role in tbe education and development of neurosurgery?
Materials and methods: A literature search was conducted to find the role of art and technology in forms of illustrations, models, or others in neurosurgery.
Results: Illustration was known as one of the tools to understand it in the past. Now, in the modern era, neurosurgical learning, training, and teaching process have integrated both art and technology throughout the process. Not only as two-dimenional drawings, art and technology have gone as far as being developed into three-dimensional models and create specific models for surgical plannings and simulations. Artificial intelligence, virtual reality, and augmented reality have also been used to achieve accurate and efficient learning process and neurosurgical care.
Discussion and conclusion: Art does take significant role in the progression of neurosurgery. When combined with technology, art give greater utility and impact through the learning, teaching process, and delivery of care in neurosurgical world.

1. Introduction

"To develop a complete mind: Study the science of art. Learn how to see. Realize that everything connects to everything else".

This exceptional statement by Leonardo da Vinci has stood the testament of time over the past several centuries to describe art and its relevance in every aspect of life including medicine (Pasipoularides, 2019). In the current neurosurgical training and teaching era, we have systematically ascertained acceptable competencies required to navigate the learning phase to become a successful surgeon. Like every medical specialty, surgery is an art, and we aim to emphasize the need to understand the deep-seated connection, art has with Neurosurgery. Art and medicine have been linked since the prehistorical era. Art has helped human to convey things that cannot be expressed by words in learning process to achieve better understanding. Ample evidence depicting neurosurgical illustrations and developments were dated from prehistorical era (Geranmayeh and Ashkan, 2008). This proves that art has been in existence over a long period and has contributed to the transfer of neurosurgical knowledge. However, combined with the rapidly evolving technology, art has taken a major role in the field of neurosurgery and offer new possibilities for the present and the near future.

We take this opportunity to felicitate the pioneering contributions by legends in multiple eras that paved way to seamlessly linked the past to the present and the future in understanding Neurosurgery via art.

2. Materials and methods

Authors conducted literature search on the involvement of art and technology in neurosurgery. Any articles relevant to the topic is included

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in this study.

3. Results and discussion

3.1. Neuroanatomy learning in the past

In the 15th century, art became popular as anatomical knowledge provided significant resource to the surgeons. Anatomical art was first popularized by Leonardo da Vinci where he was able to transform his ideas and his knowledge of medicine into anatomical drawings (Bell and Evans, 2014). da Vinci was particularly interested in the nervous system, although he also devoted his interests in anatomy and mechanical drawings. He discovered the structure of meningeal artery, frontal sinuses, and created model of brain ventricles (Pasipoularides, 2019). The model of brain ventricle, Fig. 1, showed that it was divided into three divisions (anterior, middle, and posterior) and was constructed by layered structures (Leonardo et al., 1983). Not long after, he injected wax into brain to create internal organ model, which is more accurate and closely resembling the shape of the brain ventricles we know today (Geranmayeh and Ashkan, 2008). These drawings were in 2D but da Vinci revolutionized how the 2D pictures and drawings can be brought to life in 3D akin to the current modern 3D printing technology.

Later in the 16th century, Andreas Vesalius created human anatomy textbook which included the anatomy of skull, meninges, brain, and ventricles (Fig. 2). "De Humani Corporis Fabrica" was published in 1543, which became landmark texbook in the history of medicine (Vesalius, 1998; Scatliff and Johnston, 2014). The illustrations were based on the cadaveric dissections, which would require careful observational skills before translated into drawings. His discoveries and methods were impactful in advancing the medicine world, especially to achieve understanding of central nervous system anatomy (Splavski et al., 2019). His works also inspired anatomists such as Thomas Willis who created "Cerebri Anatome", contributing to the expanding the knowledge of neuroanatomy within the era (Scatliff and Johnston, 2014).

3.2. Neuroanatomy learning in the present

Frank Henry Netter was one of the most renowned medical doctors and medical illustrators in the 20th century. He began his career by working for several pharmaceutical companies until finally he published colored atlases which are still widely used for medicine-learning purposes (Netter et al., 2014). Unlike the previously mentioned artists who used black or sepia ink, Netter used gouache to create paintings in colors, making neuroanatomy learning easier for students. He never used computer as a digital drawing medium, although he reckoned the potential it may offer in the future (Hansen et al., 1906).

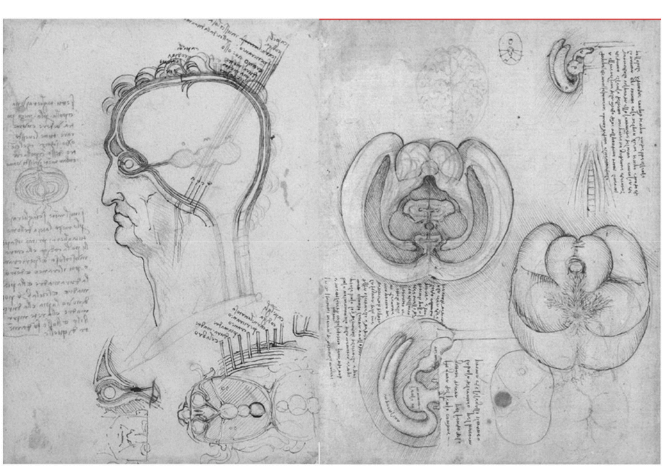

Fig. 1. Sagittal and axial view of human head by Leonardo da Vinci in 1490 and illustration of brain ventricles based on the wax model(Leonardo et al., 1983).

In the early modern days of neurosurgery, Harvey Cushing, the father of modern Neurosurgery, has added to this legacy in a phenomenal manner. His illustrations, which he produced during his entire career, however, have been less known. He created many sketches of the steps of the surgery he performed and detailed illustrations when he was in medical school, residency, and as a neurosurgeon, such as shown by Fig. 3 (Sathi et al., 1991; Wilkins, 1992; Cushing). Sketches and illustrations he made became important as they were drawn from neurosurgeon's point of view. Along the journey, he also reduced the number of mortality on the cases he operated on, which may be related to the whole learning process, including creating operative sketches (Sathi et al., 1991). One of his pupils, Franc Ingraham, also exhibited the same artistic skills as a neurosurgeon. He has been known as the founding father of pediatric neurosurgery. He was a man of many enthusiasts, including photography and painting. His illustration on suturectomy procedure was documented, showing his ability both as a neurosurgeon and as an artist (Lohani et al., 2013). Kenichiro Sugita, well-known for the Sugita head frame, created a microsurgical atlas which was illustrated by him (Sugita and Kobayashi, 1985). Table 1 shows the examples of neurosurgeons in the past who contributed in neurosurgery through art (Sathi et al., 1991; Wilkins, 1992; Cushing; Lohani et al., 2013; Sugita and Kobayashi, 1985; Adams and Schlich, 2006).

Creating illustrations for can be a laborous work for neurosurgeons as working hours are long. For commercial or scientific purposes, neurosurgeons often collaborate with professional medical illustrators or artists to produce neuroanatomy or surgical illustrations. In the earlier days, Max Brodel worked together with Harvey Cushing and Walter E. Dandy to produce various neurosurgical illustrations Patel et al. (2011) Professor Gazi Yasargil worked together with Peter Roth for "Microneurosurgery" which consisted of 6 books, first published in 1984 (Yaşargil et al., 1984; Yaşargil and Yaşargil, 1984; Yaşargil et al., 1987; Yaşargil, 1988; Yaşargil et al., 1994; Yaşargil and IVB, 1996). Professor Ossama Al-Mefty collaborated with Michael P. Schenk and Ron M. Tribell to create illustrations of his elaborated meningioma publications (Al-Mefty, 1990; Arnautovic et al., 1999; Al- et al., 2011). Professor Albert L. Rhoton worked with his fellows and illustrators (Bob Beach, Carla Lenkey, David Peace, and Margaret E. Barry) to create the well-known "Cranial Anatomy and Surgical Approaches" which is still relevant until today and used widely by neurosurgeons (Matsushima et al., 2019). This proves that in addition to outstanding cadaveric dissection work, anatomical illustrations is as important to complement the depth of understanding. Collaborative works in neurosurgery are not always easy to create, however. Neurosurgeons must work together with the artists to make sure that the proportion, size, and depth of the anatomical objects correct and representative. Thus, medical illustrators and medical doctors with artistic capabilities would be great collaborators to bridge this difficulty.

The mentioned neurosurgeons and collaborating artists used traditional media such as gouache, ink, colored pencils, and carbon dust. Currently, the utility of computer as digital illustration medium has gained significant interest for its reproducibility and time-saving capability. As a growing field, medical illustration has been popularized by many artists who exhibits terrific capability in utilizing the infinite utility of digital medium. Peter M. Lawrence is one of the most popular artists who uses digital medium to create illustrations for neurosurgical books such as the Seven AVMs and Seven Cavernomas, in which he collaborated with neurosurgeons such as Michael T. Lawton (Lawton, 2014; Lawton et al., 2022). Regardless the media, these illustrations aim to create perspective on surgical approaches including angles, hidden structures, and views that may not be seen in daily practice or surgery.

The growing digital technology also gives rise to the three-dimensional models of human anatomy. Three-dimensional models offer the capability of rotation and segmentations which allow users to appreciate the structure of neuroanatomy even more. In addition, its

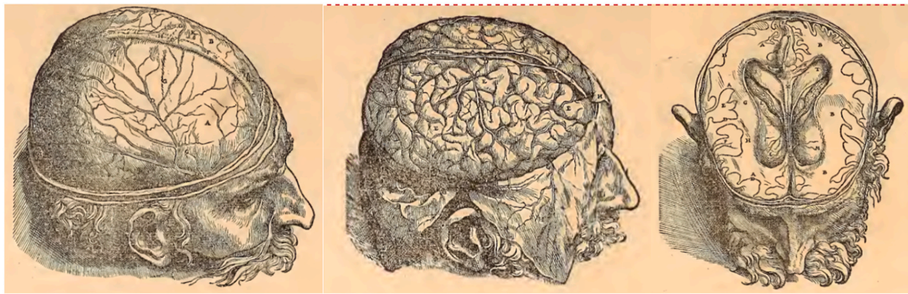

Fig. 2. The anatomy of meningeal layer and its vascularizations, brain surface, and axial cut of the brain at the level of corona radiata, respectively by Andreas Vesalius (Vesalius, 1998; Scatliff and Johnston, 2014).

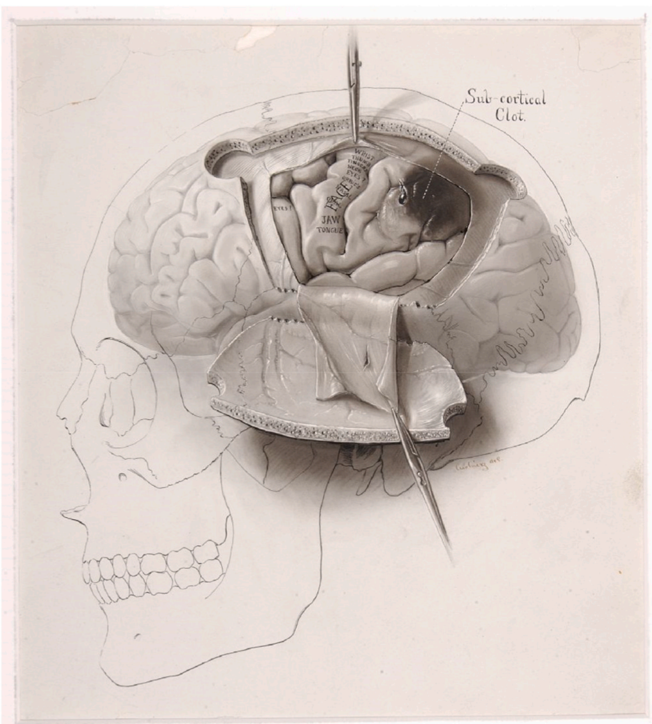

Fig. 3. Harvey Cushing's illustrations of brain, craniotomy, and subcortical clot.(Cushing).

Table 1
Examples of neurosurgeons with artistic capabilities and their contributions in neurosurgery.

No.	Neurosurgeon	Contribution in Neurosurgery
1.	Wilder Penfield	Brain mapping illustration (homunculus), architectural drawings (Adams and Schlich, 2006)
2.	Harvey Cushing	Surgical notes and anatomical illustrations (Sathi et al., 1991; Wilkins, 1992; Cushing)
3.	Franc Ingraham	Surgical notes and anatomical illustrations (Lohani et al., 2013)
4.	Kenichiro Sugita	Microsurgical atlas, development of surgical tools (Sugita and Kobayashi, 1985)

application has been used to surgical planning programs. This proves that in the modern day, art in general is still very relevant and is an integral part of neurosurgery development.

3.3. The future: art, technology, neurosurgical planning and procedures

The emergence of medical illustrations, created by illustrators or surgeons, and development of digital three-dimensional models has perpetuated the endless journey of art in the field of neurosurgery (Figs. 4 and 5). Technology has been exponentially growing and when combined with art, both has an immense potential in supporting neurosurgeons from various aspects. In neurosurgery learning process, the ability to perceive the depth of the surgical field, the ability to catch the details within the surgical field and feel the texture of different organs are mandatory. Harvey Cushing's routine of drawing on the operative reports have been important and encouraged residents and young neurosurgeons to understand its importance as every procedure had something to added to the literature. Despite the recent wide availablility of surgical videos on social media platforms which can be accessed online, the transfer of knowledge through the surgeons' perspective and notes is irreplaceable (Rilliet and Goodrich, 2010). The introduction of art, with a purpose to create operative sketches and to achieve better understandings on neuroanatomy and surgical procedures, should be encouraged. The growing demand to digitize operative records in the modern era has taken the opportunity of surgeon's ability to draw similar to the days of Harvey Cushing. A surgeon's point of view is important, yet it is not only what was seen, but also what was perceived and what can be conveyed in a different form to make people understand.

The application of art and technology have also expanded to converting digital models to real-life models. Printed models of cranium, brain, and vasculatures have been produced for anatomy learning especially prior surgery. For example, prior separation of craniopagus twins, three-dimensional imaging technology was used to create printed models of brain and vasculatures for surgical planning. This helped the entire surgical team to visualize, understand and decide the safest approach and dissection (Schreiber et al.).

Materials used to bring the anatomy to life vary, although recent breakthroughs have paved way to produce models which resemble the likeness of human tissues. Beside trainings, the development of these printed models has also been used to create pathological cranial models for surgical simulation before conducting the real surgery. These models are commercially available for training purposes and more of the pathological variations are on developments. Additionally, models also aid to fill the gaps where number of cases are unable to meet and to bridge this disparity. However, the use of three-dimensional printing models have yet to be widely used in many countries due to multiple reasons (Thiong'o et al., 2021).

Other technological advances have allowed the development of intraoperative navigation as an essential adjunct in Neurosurgery in particular. This technology allows the projection of registered CT or MRI data to patients' cranial or spine structure. Usually, surgeon can point location of the intended pathological lesion or point by using a probe, but recent technological advancement allows robot-assist in determining the location and trajectory of the lesion. This is especially useful in stereotactic surgeries, where accuracy is key and error can be minimized (Mao et al., 2021).

Artificial intelligence (AI) and machine learning (ML) have gained

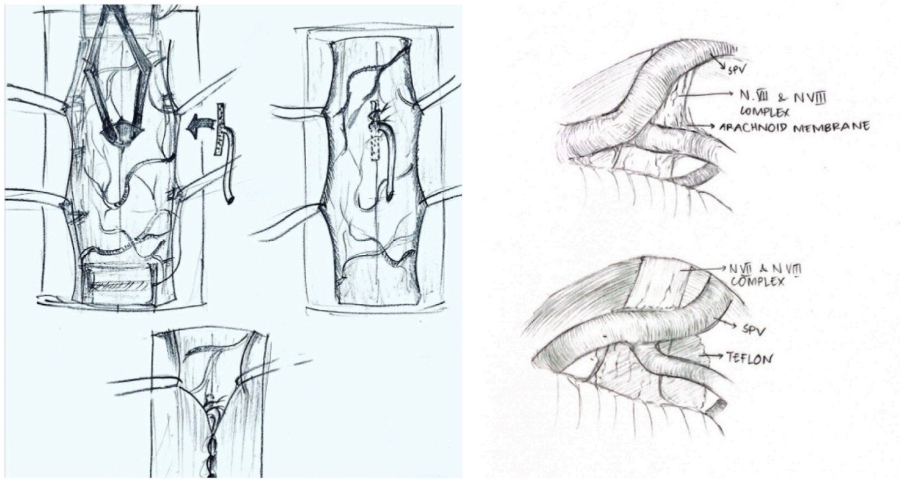

Fig. 4. Surgical illustrations of neurosurgical procedures made by authors (left: syringopleural shunt, right: microvascular decompression), influenced by the work of the Giants of Neurosurgery.

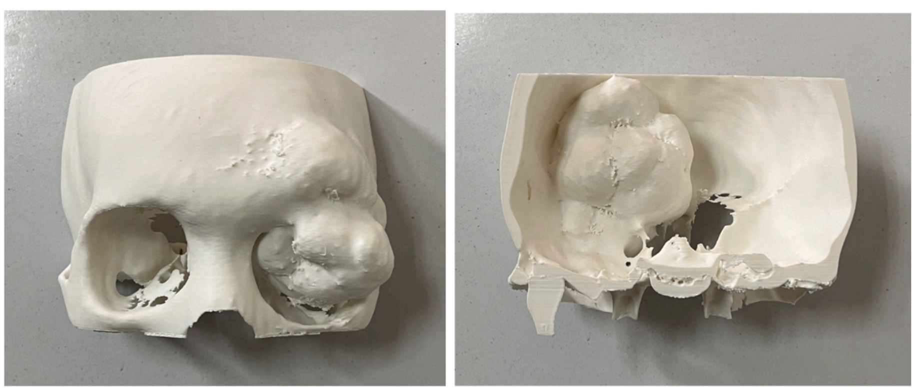

Fig. 5. Printed model of hyperostosis caused by meningioma, front and inner view.

great importance in neurosurgery. Neurosurgery involves various digital data that can be analysed and processed to make clinical decisions such as CT scan, MRI, digital subtraction angiography (DSA), and other clinical data. Despite long years of training, technical errors can still happen in this field due to mental and physical fatigue. AI and ML can be integrated within the practice to reduce time, minimize error, help neurosurgeons making clinical decisions, whether pre-operatively (creating diagnosis), intra-operatively (enhancing surgeon's performance), and post-operatively (predicting prognosis and complications) (Mofatteh, 2021). Brain tumor surgery, functional, vascular, and spine surgery have integrated AI to create algorithm in delivering neurosurgical care (Buchlak et al., 2020; Danilov et al., 2021; El-Hajj et al., 2023). Beside delivering neurosurgical care, AI and ML are also useful in research, for example creating neuronal bypass from cortex to spinal cord in damaged spinal cord (Mofatteh, 2021).

Virtual reality (VR) technology has been popular in medicine, especially for training and learning process by immersing the user to the 3-dimensional VR realm. VR has been developed to create patient-specific model for complex cases to increase diagnostic accuracy and overcome the lack of resources or materials for training. Augmented reality (AR) is newer, in which virtual objects are combined with physical reality surrounding the users. Example use of AR is navigation system where the navigation and surgical view is merged on the operative field, thus surgeon do not have to repeatedly switching from looking at the surgical view to navigation screen (Kazemzadeh et al., 2023).

In addition, art has also been used to improve patient outcomes perioperatively through expressive art therapy (ExAT). Although not directly linked to a neurosurgeon's training or skills, ExAT has been used to address issues which affect patients during hospitalisation, such as stress, depression, physical pain, and discomfort through creative processes, including drawing and painting. ExAT has been seen to improve the experience in cancer care by tackling the psychological symptoms of patients during treatment and recovery. (LaCreta) The benefits of ExAT have also been replicated with patients suffering from neurological injury such as stroke survivors, in which ExAT may help emotional aspects, physical rehabilitation of the affected limbs, and also social interactions (Carter et al., 2023; Reynolds, 2012). Unfortunately, the full extent of ExAT in neurosurgery has not been yet determined, due to the lack of systematic clinical studies (Carter et al., 2023). But from all the previous findings it can be ascertained that ExAT can potentially have a vital role in yielding a more holistic care to patients in clinical neuroscience.

It becomes evident that art and technology have helped neurosurgery to develop and aid learning process of students, residents, and neurosurgeons. The utility will expand more in the future to offer smooth workflow and help in minimize the potential errors in real life surgery. It is possible that through art and technology development, surgery will be even safer and less invasive compared to what encounter on a day-to-day basis.

4. Conclusion

Art has taken a significant role in the education and development of modern neurosurgery. Traditionally, art was useful for illustrating anatomical structures and surgical steps through two-dimensional drawings by anatomists, medical doctors, and neurosurgeons. The creation of operative illustrations should be encouraged to achieve higher level of understanding and to convey operator's point of view, especially to residents and young neurosurgeons, regardless using traditional media or digital. Current technological advancements allow anatomy to be represented as three-dimensional models which resemble the alikeness of tissue consistency. These are becoming more available in the market for neurosurgical training and the gap that apparently exists between the developed and developing countries will eventually narrow down. Additionally, technology such as AI, VR, and AR also allow the creation of patient-specific models for surgical planning, simulation prior surgical practice, and improve surgical workflow aiming to reduce operative morbidity and mortality without an iota of doubt.

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Declaration of competing interest

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References

Adams, A., Schlich, T., 2006. Design for control: surgery, science, and space at the royal victoria hospital, Montreal, 1893–1956. Med. Hist. 50, 303–324. https://doi.org/10.1017/S0025727300010000.

Al-Mefty, O., DeMonte, F., McDermott, M.W. (Eds.), 2011. Al-Mefty's Meningiomas, second ed. Thieme Medical, New York.

Al-Mefty, O., 1990. Clinoidal meningiomas. J. Neurosurg. 73, 840–849. https://doi.org/10.3171/jns.1990.73.6.0840.

Arnautovic, K.I., Al-Mefty, O., Husain, M., 1999. Meningiomas of the ventral foramen magnum. FOC 6, E7. https://doi.org/10.3171/foc.1999.6.6.8.

Bell, L.T.O., Evans, D.J.R., 2014. Art, anatomy, and medicine: is there a place for art in medical education?: art, Anatomy, and Medical Education. American Association of Anatomists 7, 370–378. https://doi.org/10.1002/ase.1435.

Buchlak, Q.D., Esmaili, N., Leveque, J.-C., Farrokhi, F., Bennett, C., Piccardi, M., Sethi, R. K., 2020. Machine learning applications to clinical decision support in neurosurgery: an artificial intelligence augmented systematic review. Neurosurg. Rev. 43, 1235–1253. https://doi.org/10.1007/s10143-019-01163-8.

Carter, A.M., Dioso, E.R., Romero, B., Clinker, C.E., Lucke-Wold, B., 2023. Complementary Medicine and Expressive Arts Therapy: Adjuvant for Recovery Following Neurosurgical Procedures. OBM Integr Complement Med 08 1–14. https://doi.org/10.21926/obm.icm.2301007.

H. Cushing, Harvey Cushing drawing of the brain showing a sub-cortical clot, Yale University Library (n.d.).https://collections.library.yale.edu/catalog/15951324..

Danilov, G.V., Shifrin, M.A., Kotik, K.V., Ishankulov, T.A., Orlov, Y.N., Kulikov, A.S., Potapov, A.A., 2021. Artificial intelligence in neurosurgery: a systematic review using topic modeling. Part I: major research areas. Sovrem Tekhnologii Med 12, 106–112. https://doi.org/10.17691/stm2020.12.5.12.

El-Hajj, V.G., Gharios, M., Edström, E., Elmi-Terander, A., 2023. Artificial intelligence in neurosurgery: a bibliometric analysis. World Neurosurgery 171, 152–158.e4. https://doi.org/10.1016/j.wneu.2022.12.087.

Geranmayeh, F., Ashkan, K., 2008. Mind on Canvas: anatomy, signs and neurosurgery in art. Br. J. Neurosurg. 22, 563–574. https://doi.org/10.1080/02688690802109820.

Hansen, J.T., Frank, H., Netter, M.D., 1991. The artist and his legacy. Clin. Anat. 19, 481–486. https://doi.org/10.1002/ca.20358, 2006.

Kazemzadeh, K., Akhlaghdoust, M., Zali, A., 2023. Advances in artificial intelligence, robotics, augmented and virtual reality in neurosurgery. Front. Surg. 10, 1241923 https://doi.org/10.3389/fsurg.2023.1241923.

M. LaCreta, Mindfulness and Expressive Arts Therapies in Cancer Care, (n.d.).

Lawton, M.T., 2014. Seven AVMs: Tenets and Techniques for Resection. Thieme, New York.

Lawton, M.T., Graffeo, C.S., Srinivasan, V.M., Hendricks, B.K., Catapano, J.S., Scherschinski, L., Lawrence, P.M., Larson Keil, K., VanBrabant, D., Hickman, M.D., 2022. Seven cavernomas and neurosurgical cartography, with an assessment of vascular waypoints. J. Neurosurg. 1–15. https://doi.org/10.3171/2022.8.JNS221706.

Leonardo, Keele, K.D., Roberts, J., 1983. Leonardo da Vinci: anatomical drawings from the Royal Library, Windsor Castle. Metropolitan Museum of Art, New York.

Lohani, S., Cohen, A.R., Franc, D., 2013. Ingraham and the genesis of pediatric neurosurgery: historical vignette. PED 11, 727–733. https://doi.org/10.3171/2013.3.PEDS12476.

Mao, J.Z., Agyei, J.O., Khan, A., Hess, R.M., Jowdy, P.K., Mullin, J.P., Pollina, J., 2021. Technologic evolution of navigation and robotics in spine surgery: a historical perspective. World Neurosurgery 145, 159–167. https://doi.org/10.1016/j.wneu.2020.08.224.

Matsushima, T., Richard Lister, J., Matsushima, K., De Oliveira, E., Timurkaynak, E., Peace, D.A., Kobayashi, S., 2019. The history of Rhoton's Lab. Neurosurg. Rev. 42, 73–83. https://doi.org/10.1007/s10143-017-0902-4.

Mofatteh, M., 2021. Sir william dunn school of pathology, medical sciences division, university of oxford, south parks road, oxford OX1 3RE, United Kingdom, lincoln college, university of oxford, turl street, oxford OX1 3DR, United Kingdom, neurosurgery and artificial intelligence. AIMSN 8, 477–495. https://doi.org/10.3934/Neuroscience.2021025.

Netter, F.M., Friedlaender, G.E., Netter, Frank H., 2014. MD and a brief history of medical illustration. Clin. Orthop. Relat. Res. 472, 812–819. https://doi.org/10.1007/s11999-013-3459-8.

Pasipoularides, A., 2019. Emulating Leonardo da Vinci (1452–1519): the convergence of science and art in biomedical research and practice. Cardiovasc. Res. 115, e181–e183. https://doi.org/10.1093/cvr/cvz275.

Patel, S.K., Couldwell, W.T., Liu, J.K., 2011. Max Brödel: his art, legacy, and contributions to neurosurgery through medical illustration: historical vignette. JNS 115, 182–190. https://doi.org/10.3171/2011.1.JNS101094.

Reynolds, F., 2012. Art therapy after stroke: evidence and a need for further research. Arts Psychother. 39, 239–244. https://doi.org/10.1016/j.aip.2012.03.006.

Rilliet, B., Goodrich, James Tait (Eds.), 2010. Neurosurgical Operative Atlas, 2nd Edn—Pediatric neurosurgery.: Thieme, New York, Hardcover (ISBN 978-1-58890-510-9), Acta Neurochir, vol. 152, pp. 181–182. https://doi.org/10.1007/s00701-009-0545-5.

Sathi, S., Rossitch, E., Moore, M.R., Black, P.McL., 1991. Harvey Cushing's postoperative sketches of pediatric brain tumors. Child's Nerv. Syst. 7, 56–58. https://doi.org/10.1007/BF00263836.

Scatliff, J.H., Johnston, S., 2014. Andreas Vesalius and Thomas Willis: their anatomic brain illustrations and illustrators. AJNR Am J Neuroradiol 35, 19–22. https://doi.org/10.3174/ajnr.A3766.

J.E. Schreiber, H. Rudy, J.T. Goodrich, M. Tepper, Separating Craniopagus Twins: A 4 Stage Approach Using 3D Imaging Technology, (n.d.).

Splavski, B., Rotim, K., Lakičević, G., Gienapp, A.J., Boop, F.A., Arnautović, K.I., 2019. Andreas Vesalius, the predecessor of neurosurgery: how his progressive scientific achievements affected his professional life and destiny. World Neurosurgery 129, 202–209. https://doi.org/10.1016/j.wneu.2019.06.008.

Sugita, K., Kobayashi, S., 1985. Microneurosurgical Atlas. Springer Berlin Heidelberg, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-61669-3.

Thiongo, G.M., Bernstein, M., Drake, J.M., 2021. 3D printing in neurosurgery education: a review. 3D Print Med 7, 9. https://doi.org/10.1186/s41205-021-00099-4.

Vesalius, A., 1998. On the fabric of the human body: a translation of De humani corporis fabrica libri septem. In: Book I: the Bones and Cartilages, Norman Pub. San Francisco.

Wilkins, R.H., 1992. American association of neurological surgeons. Neurosurgical Classics, American Association of Neurological Surgeons, Park Ridge, Ill.?.

Yaşargil, M.G., 1988. Microneurosurgery. IIIB: AVM of the Brain, Clinical Considerations, General and Special Operative Techniques, Surgical Results, Nonoperated Cases, Cavernous and Venous Angiomas, Neuroanesthesia: 191 Tab. Thieme, Stuttgart.

Yaşargil, M.G., Ivb, Microneurosurgery, 1996. Microsurgery of CNS Tumors: Instrumentation and Equipment, Laboratory, Training, Surgical Approaches, Strategies, Tactics and Techniques, Surgery and Results of Extrinsic and Intrinsic Tumors, Interventional Neuroradiology, Neuroanesthesia, Complications. Thieme, Stuttgart.

Yaşargil, M.G., Yaşargil, M.G., 1984. Microneurosurgery. II: Clinical Considerations, Surgery of the Intracranial Aneurysms and Results. Thieme, Stuttgart New York.

Yaşargil, M.G., Yaşargil, M.G., Microneurosurgery, I., 1984. Microsurgical Anatomy of the Basal Cisterns and Vessels of the Brain, Diagnostic Studies, General Operative Techniques and Pathological Considerations of the Intracranial Aneurysms. Thieme, Stuttgart.

Yaşargil, M.G., Teddy, P.J., Valavanis, A., Duvernoy, H.M., Yaşargil, M.G., 1987. Microneurosurgery. IIIA: AVM of the Brain. Thieme, Stuttgart ; New York.

Yaşargil, M.G., Adamson, T.E., Yaşargil, M.G., 1994. Microneurosurgery. IVA: CNS Tumors: Surgical Anatomy, Neuropathology, Neuroradiology, Neurophysiology, Clinical Considerations, Operability, Treatment Options. Thieme Medical Publishers, Stuttgart ; New York : New York. Georg Thieme Verlag.