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The arterial circle described by Willis, and the contribution of his successors

O círculo arterial descrito por Willis e a contribuição de seus sucessores

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ABSTRACT

The description of the base of the human brain and its arteries that form a circle or polygon, as described and depicted by Thomas Willis and collaborators (1664), and that received his name – 'circle of Willis', has a long history, where many renowned preceding authors are included – the pre-Willisian anatomists, among which the names of Giulio Casserio (1627), Johann Vesling (1647) e Johann Jakob Wepfer (1658) deserve to be highlighted. However, despite a complete description and correct depiction of the arterial components of the circle, their naming lagged behind. After Willis, a large number of renowned authors – the post-Willisian anatomists, studied this formation further. This period begun with a poor contribution of Isbrand van Diemerbroeck (1672). Next appeared authors who provided names that became ephemeral, followed by those who presented designations that would remain permanently. Among the latter must be cited initially Joseph Lieutaud (1742) and Albrecht von Haller (1756), followed by Xavier Bichat with his posthumous work (1803), and finally the definitive names being established by Jean Cruveilhier (1834), this period closing with Henry Gray's book (1858), who consolidated the knowledge on the subject.

Keywords: Willis, arterial circle, nomenclature

RESUMO

A descrição da base do cérebro humano e das artérias que formam um círculo ou polígono, como descrito e ilustrado por Thomas Willis e colaboradores (1664) e que recebeu seu nome - 'círculo de Willis', tem uma longa história, onde constam muitos autores de renome que o precederam – os anatomistas pré-Willisianos, entre os quais os nomes de Giulio Casserio (1627), Johann Vesling (1647) e Johann Jakob Wepfer (1658) merecem ser destacados. Entretanto, apesar da descrição completa e ilustração correta dos componentes arteriais do círculo, a denominação dos mesmos ficou atrasada. Após Willis, um grande número de autores renomados – os anatomistas pós-Willisianos, continuaram a estudar essa formação. Este período começou com uma contribuição pobre de Isbrand van Diemerbroeck (1672). A seguir apareceram autores que proveram nomes que se mostraram efêmeros, seguidos por aqueles que apresentaram designações que iriam permanecer de modo permanente. Entre os últimos devem ser citados inicialmente Joseph Lieutaud (1742) e Albrecht von Haller (1756), seguidos por Xavier Bichat com sua obra póstuma (1803), e finalmente, os nomes definitivos sendo estabelecidos por Jean Cruveilhier (1834), o período fechando com o livro de Henry Gray (1858), que consolidou o conhecimento sobre o tema.

Palavras-chave: Willis, círculo arterial, nomenclatura

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INTRODUCTION

The arterial circle (or polygon) of Willis is formed by the internal carotid artery (ICA), the anterior cerebral arteries (ACA) (A1), the posterior cerebral arteries (PCA) (P1), the tip of the basilar artery (BA), and the anastomoses that interconnect them, the anterior communicating artery (ACoA) and the posterior communicating arteries (PCoA), establishing links between the carotidal system, and between the carotid and vertebrobasilar systems, i.e., between the right-left and anterior-posterior circulations respectively (Figure 1)[1,2,3] . The arterial circle as described by Willis, and bearing his name, "and Wren's figure of the base of the brain gives an accurate though somewhat stylized view of the arterial circle"[4], and came to constitute a paradigmatic pattern recognized until the present days (Box).

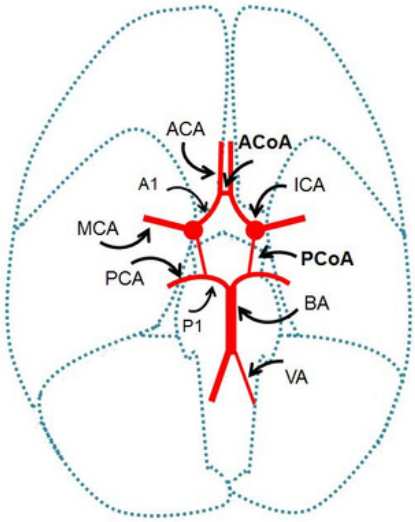

Figure 1. Simplified schema of the brain with projection of the arterial circle (of Willis) (based on Gray's "Anatomy of the Human Body")[2] (from Engelhardt and Levy, 2021 – with permission)[1].

ICA=internal carotid artery, ACA=anterior cerebral artery (A1=first segment), MCA=Middle cerebral artery, PCA=posterior cerebral artery (P1=first segment), BA=basilar artery, VA=vertebral arteries, and the anastomotic arteries, ACoA=anterior communicating artery, and PCoA=posterior communicating artery

Thomas Willis (1621-1675), British physician, studied with the collaboration of the physicians Richard Lower, Thomas Millington, and Christopher Wren, the nervous system of man and of experimental animals, which resulted in an advanced knowledge of the gross structure of the nervous system, its coverings, and circulation, published in his *Cerebri Anatome* (1664). There, he described the arteries forming a circle or polygon at the base of the brain, which later was named after him [circle of Willis]. This circle resulted from the branching and anastomosing of the cervicocephalic arteries, the two carotid and the two vertebral arteries. At the level of the base of the brain the trunks of the intracranial [internal] 'carotid arteries' (*arteriae carotidis*) divide in an 'anterior branch' [ACA] and a 'posterior branch' [PCoA] (*ramum anteriorem et posteriorem*), the anterior branch of each side join [ACoA], and then course forward, the 'posterior branches' [PCoA] join with the branches [PCA] of the trunk [BA] resulting from the fusion of the 'vertebral arteries' (*arteriae vertebrales*) [VA]. The basal view of the brain and its vasculature were depicted by Christopher Wren, physician and architect, and excellent draughtsman[1,4,6]. The arterial circle was named after the author – "circle (or polygon) of Willis"[41,42], a designation that endures until the present days.

Box. The 'arterial circle' as described by Willis.

A former paper focused on the analysis of the works on the subject of pre-Willisian anatomists, comprising Mondino de Luzzi (1316), Berengario da Carpi (1520), Andreas Vesalius (1543), Realdo Colombo (1559), Gabriele Falloppio (1561), Giulio Casserio (1627), Johann Vesling (1647), and Johann Jakob Wepfer (1658), with emphasis on the last three authors, culminating with the establishment of the anatomy of the arterial circle, described and illustrated in Thomas Willis' book (1664)[1, 5] . This period encompassed almost three and a half centuries.

Besides the description and the illustration of the anatomy of the circle (or polygon), the name of the arterial components of the circle should also be provided. However, at the time, most were only described, and the name of just one component was given – that of the intracranial 'internal carotid artery' [ICA], besides the closely related intracranial 'vertebral arteries' [VA], the union of which originates the common trunk of the 'basilar artery' [BA], which takes part of the structure of the circle, but remained unnamed, in the same way as the other described and depicted component arteries, which also had not received a specific denomination[1,6] .

Here it will be described the additional contributions of the post-Willisian anatomists, mainly related to the denomination of the arterial components of the circle that remained without a proper name, up until the point when the current nomenclature became established. The work of these anatomists lasted almost two additional centuries.

THE DESCRIPTIONS FOLLOWING THAT OF WILLIS

After the publication of Willis' book, a large number of anatomists continued to study this subject, mentioning, to a variable extent, the existing findings. Among the selected ones, those who provided new information, i.e., the definitive names of the arterial components of the circle, will be commented on with more detail, while the others, despite their significance, will only be mentioned briefly.

Isbrand van Diemerbroeck (1609-1674), Dutch physician and anatomist, published the "Anatomy of the Human Body" (*Anatome Corporis Humani*) (1672)[7].

He described a complete arterial circle, but new additional information in relation to Willis', regarding denomination, was not provided. No illustration was presented.

Thomas Gibson (1647-1722), English physician and anatomist, authored "The Anatomy of Humane Bodies Epitomized' (1682)[8].

He described a complete arterial circle, added the term 'vertebral trunk', replaced later for 'basilar artery'. The book was illustrated with a figure copied from Willis, as he acknowledged.

Raymond Vieussens (1641-1716), French physician and anatomist, published his "General Neurography" (*Neurographia Universalis*) (1684)[9].

Described a complete arterial circle, named the 'cervical artery' (*arteria cervicalis*), and the 'arteriosus channel' (*canalis arteriosus*), later replaced for 'basilar artery', and 'posterior communicating artery', respectively. He provided two illustrations of the base of the brain, which completed the circle in a complementary way.

Govard Bidloo (1649-1713), Dutch physician, and anatomist, published the "Anatomy of the Human Body' (*Anatomia Humani Corporis*) (1685)[10].

He did not provide a description. There is an illustration showing a complete arterial circle, although atypical, in which components remained unnamed, as stated in the caption.

Pierre Dionis (1643-1718), French surgeon and anatomist, authored 'The Anatomy ofMan According to the Circulation of the Blood' (*L'Anatomie de l'Homme Suivant la Circulation du Sang*) (1690)[11].

The description of the arteries of the base of the brain is incomplete. The illustration was copied from Bidloo, without caption.

Humphrey Ridley (1653-1708), British physician and anatomist, published the "Anatomy of the Brain" (1695), the first book on the human brain written originally in English language[12].

He described an incomplete arterial circle, introduced the term 'communicant branches' to designate the 'posterior communicating arteries'. An illustration was provided demonstrating an atypical and incomplete arterial circle.

William Cowper (ca 1666-1709), English surgeon and anatomist, published 'The Anatomy of Human Bodies" (1698)[13].

The description did not add new contribution related to denomination of the arterial components. He illustrated his work, initially, with Bidloo's complete, although atypical circle. Next, he provided another figure, incomplete and atypical, already published by Ridley, with the components cited in the caption.

Frederik Ruysch (1638-1731), Dutch physician and anatomist, produced "Twelf Problematic Anatomic Letters" (*Epistola Anatomica, Problematica, Duodecima*) (1699)[14].

He described partially the arterial circle, without introduction of new terms. The book was illustrated with a complete circle.

Herman Boerhaave (1668-1738), Dutch physician, chemist, and botanist, published the book "Medical Foundations" (*Institutiones Medicae*) (1727)[15,16].

Described without details the arterial circle, without the introduction of new terms. He did not provide an illustration.

Joseph Lieutaud (1703-1780), French physician and anatomist, in his book "Anatomical Essays" (*Essais Anatomiques*) (1742) he describes the [intracranial] 'internal carotid' and 'vertebral' arteries. The vertebral arteries, after a short course, approach and join to form a single artery, "which is named basilar artery" (*...qu'on nomme basilaire*) [BA], which divides into two branches [PCA]. The internal 'carotid artery' [ICA] divides into two branches, an internal [anterior] and the other external; the 'internal [anterior] branch' [ACA] approaches the similar one of the opposite side, and exchanges some 'anastomosis' [ACoA], then following forward; before the division, the internal carotid artery emits a branch that communicates [PCoA] with the 'branches' [PCA] of the 'basilar artery'. He provided some well-drawn plates, but none of the base of the brain and its arteries[17].

He described the components of the arterial circle, introduced the term 'basilar artery' (*artère basilaire*). He did not provide an illustration of the circle.

Albrecht von Haller (1708-1777), Swiss physician, and anatomist, pupil of Herman Boerhaaven, in his "Anatomical Images" (*Icones Anatomicae*) (1756) includes the "Arteries of the Brain" (*Arteriae Cerebri*) (Fascicle VII), where the base of the brain and the arteries there present are displayed (Plate I) The intracranial segment of the 'internal carotid artery' divides into an anterior and a posterior branch, the 'anterior branch of the carotid artery' or 'artery of the corpus callosum' (*anterior carotidis internae ramus sive arteria corporis callosi*) [ACA] present an anastomosis [ACoA] [absent in caption], then follows forward. The intracranial segment of the 'vertebral arteries' join together to form the 'common vertebral trunk' (*truncum vertebralium communem*), also named 'cervical' (according to Vieussens) or 'basilar' (*basilarem*) [according to Lieutaud][BA], which at the anterior border of the pons divide into four branches, two of which are the 'posterior cerebral arteries' or 'deep arteries' (*arteria posterior aut profunda cerebri*) [PCA]; there are anastomoses between those and the internal carotid arteries, the 'communicating arteries or Willis' circle (*arteriae communicantes sive circulus Willisii*) [PCoA][18]. Another book was published posthumously, the "Anatomical Descriptions of the Arteries of the Human Body" (1813), edited by John Collins Warren, American surgeon and anatomist, based on the last London edition (1811), with additions and revisions, illustrated by coloured engravings selected from the *Icones*, with the division of the arteries adopted from Xavier Bichat's *Anatomie Générale*. There, are described the 'internal carotid artery', or 'cerebral artery', the intracranial segment emitting the 'communicating artery' [PCoA], and an 'anterior branch' or 'callosal artery' [ACA], which inosculates with the opposite one through a short and transverse 'communicating branch' [ACoA]. Next are described the intracranial parts of the 'vertebral arteries' [VA] that join to form the 'basilar artery' [BA], which divides into four branches, the 'superior branches' [PCA] unite with

the 'communicating arteries' [PCoA], anastomosing with the internal carotid arteries, and "forming the great circle of Willis"[19,20].

He described the components of the arterial circle, and introduced the term 'artery of the corpus callosum' (later substituted by the term 'anterior cerebral artery'), named the 'posterior cerebral artery' (or 'deep cerebral artery') [PCA], and the [posterior] 'communicating arteries' [PCoA]. Provided a complete illustration. Both books present similar descriptions and illustrations.

Giovanni Domenico Santorini (1681-1737), Italian physician and anatomist, published the "Anatomical Observations" (*Observationes Anatomicae*) (1724), where there is a partial description of the arterial circle[21]. The corresponding illustration was presented in the 'Jo. Dominici Santorini's Principal Seventeen Anatomical Plates' (*Jo: Dominici Santorini Anatomici Summi Septemdecim Tabulae*) (1775), drawn by the painter Giovanni Baptista Piazzetta (intended to be the 2nd volume of the "Anatomical Observations"), compiled and published posthumously by his pupil Michael Girardi, with the collaboration of Giambettista Morgagni, where all unreleased anatomical observations and related illustrations are found[22,23,24].

He described some components of the arterial circle in the first book. No illustration was provided. Later, posthumously, another book was released, where the components of the circle are described, however without new names. An illustration of the base of the brain is displayed, and the arteries of the circle are partially seen.

Félix Vicq d'Azyr (1748-1794), French physician and anatomist, in his book "Tratise of Anatomy" (*Traité d'Anatomie*) (Plate XIX) (1786) are displayed the arteries of the base of the brain, drawn after have being injected. There, it is represented the 'internal carotid artery or cerebral' (*artère carotide interne ou cérébrale*) [ICA], cut after the last curvature, giving origin to the 'communicating artery' (*artère communicante*) [PCoA], which joins with the main branches [PCA] of the 'basilar artery' (*artère basilair*) [BA]. The carotid artery gives origin to two branches, an anterior and an external - the anterior branch curves over the optic nerve, and receives the name of 'callosal artery' (*artère calleuse*) [ACA], which approaches the opposite one, both becoming connected by a short anastomosis [ACoA] [depicted], then running forwards. He further describes the intracranial 'vertebral arteries', converging and forming the 'basilar artery' [BA], which ramifies cephalically into the 'deep cerebral arteries - posterior or deep of Haller) (*artère profonde du cerveau – posterior sive profunda Halleri*) [PCA], which gives origin to the 'communicating arteries' (*artère communicante*) [PCoA]. The superb illustrations were drawn and engraved by Alexandre Briceau, draftsman to the anatomy cabinet of Alfort Royal Veterinary School[25,26].

He described the components of the arterial circle, without new contribution to the nomenclature. There is a complete and well-drawn illustration.

Samuel Thomas von Soemmerring (1755-1830), German physician, and anatomist, published "On the Structure of the Human Body" (*De Corporis Humani Fabrica*) (1792, 1800) in six volumes, among them one about the arteries[27,28].

He described the components of the arterial circle, without introducing new terms. He did not provide an illustration.

Marie-François-Xavier Bichat (1771-1802), French anatomist and pathologist, in his book "Treatise of Descriptive Anatomy" (Volume IV) (*Traité d'Anatomie Descriptive* [*Tome IV*] (1803) (completed posthumously and published by Matthieu François Régis Buisson, and Philibert Joseph Roux, ex-pupils, who were collaborating with Bichat's work), the arterial circulation of the base of the brain is described, comprising the intracranial 'internal carotid artery' [ICA] and its course, ramifying into the 'anterior cerebral artery' [ACA] (and the middle cerebral artery), which runs forwards and anastomoses with the opposite one by a short transversal branch, the 'anterior communicating' [artery] ([*artère*] *communiquante antérieur*) [ACoA]. He, further described the course of the intracranial 'vertebral arteries' [VA] that join to form the 'basilar artery' [BA], which ramifies into the 'posterior cerebral arteries' [PCA], the anterior [carotid] and posterior [vertebrobasilar] circulation are in communication through the 'posterior communicating' [arteries] ([*artère*] *communiquante postérieur*) [PCoA]. He regards these anastomoses as a manner to make the distribution of the blood to the brain livelier and uniform. He added that such anastomoses make the arterial cerebral systems one whole, which may even supplement each other in certain cases. No illustration was provided[29,30,31].

He described the components of the arterial circle, and introduced the terms 'anterior cerebral artery' and 'anterior communicating' artery. This description is a close approximation to the present-day denomination of the components of the arterial circle. An illustration was not provided.

The brothers Bell, Scottish surgeons, anatomists, and skilled draughtsmen made major contributions to the anatomy of the human body, including of the nervous system, and of its vasculature.

Charles Bell (1774-1842), authored and illustrated the "Anatomy of the Human Body" (vol III – 'The Anatomy of the Nervous System') (1803), where he inserted a sketch of the arteries of the base of the brain, with a complete circle ('circle of Willis'), and identified some components[32]. Later he published the "Engravings of the Arteries" (1812), showing the base of the brain and the local arteries (Plate V), accompanied by an explanatory caption[33], a

complementary book to illustrate the already published "Anatomy of the Human Body" (vol II – 'The Anatomy of the Heart and Arteries') (1808), authored by his older brother John Bell (1763-1820), where there is a full description of arteries of the base of the brain[34,35,36].

Initially, Charles Bell provided a sketch of the complete circle in the book he authored. Later, the description of the components of the arterial circle was presented by John Bell, without new denomination. The illustration, with a caption, also without new names, was published in a complementary book, produced by Charles Bell.

Jean Cruveilhier (1791-1874), French anatomist and pathologist, in his "Descriptive Anatomy" (*Anatomie Descriptive*) (1834) describes the 'internal carotid arteries', ramifying into three branches – one anterior, the 'anterior cerebral artery' (or 'artery of the corpus callosum') (*artère cérébrale antérieur*), one external, and one posterior, the 'posterior communicating artery' (*artère communiquante postérieure*). The anterior cerebral artery approaches the opposite one, becoming connected by an anastomotic branch, the 'anterior communicating artery' (*artère communiquante antérieure*), after which they continue their course forward. Next, he describes the 'posterior communicating artery' or Willis' communicating artery, which arises from the internal carotid artery, bilaterally, and course backward to join the 'posterior cerebral arteries' (*artères cérébrales postérieures*), terminal branches of the 'basilar trunk' (*tronc basilaire*), the latter constituted by the junction of the intracranial 'vertebral arteries' [VA]. He emphasizes the anastomosis at the base of the brain, forming an arterial hexagon (*hexagone artérial*). He also underlines that from this polygon, as from a centre, all arteries of the brain leave. Finally, he ponders that considering these large anastomotic communications, one only of the four arterial trunks may suffice for the cerebral circulation in the absence of the other three. The description is perfect, but no illustration was presented[37].

He described the components of the arterial circle with the complete present-day denominations, in a precise manner. However, no illustration was provided.

Jones Quain (1796-1865), Irish anatomist, and **William James Erasmus Wilson** (1809-1884), Scottish surgeon and anatomist, published their "A Series of Anatomical Plates" (including 'The Vessels of the Human Body') (1836–42)[38].

They described the components of the arterial circle, without introducing a new term. A well-done illustration was provided.

Henry Gray (1827-1861), British anatomist and surgeon, published the first edition of his "Anatomy – Descriptive and Surgical" (1858), based on dissections he performed with the collaboration of Henry Vandyke Carter, anatomist, surgeon, and skilled draughtsman, who also provided the drawings that illustrate the book. There, it is described and displayed correctly the base of the brain and the vessels related to the arterial circle, comprising the 'anterior cerebral artery' [ACA] that arises from the 'internal carotid artery' [ICA], passes forwards, and connects soon after its origin with its congener of the opposite side by a short anastomosing trunk, the 'anterior communicating artery' [ACoA], then the 'posterior communicating artery' [PCoA] arises from the back part of the internal carotid, runs backwards, and anastomoses, on each side, with the 'posterior cerebral artery' [PCA], terminal branches of the 'basilar artery' [BA], the latter formed by the junction of the intracranial 'vertebral arteries' [VA]. He comments, regarding the circle of Willis: "The remarkable anastomosis which exists between the branches of the internal carotid and vertebral arteries, at the base of the brain, constitutes the circle of Willis...It is by this anastomosis that the cerebral circulation is equalized, and provision made for effectually carrying it on, if one or more of the branches are obliterated". The book is still published under the title "Gray's Anatomy" (Figure 2)[39,40] .

He described the components of the arterial circle, with the present-day designations. A complete illustration of the arterial circle was provided.

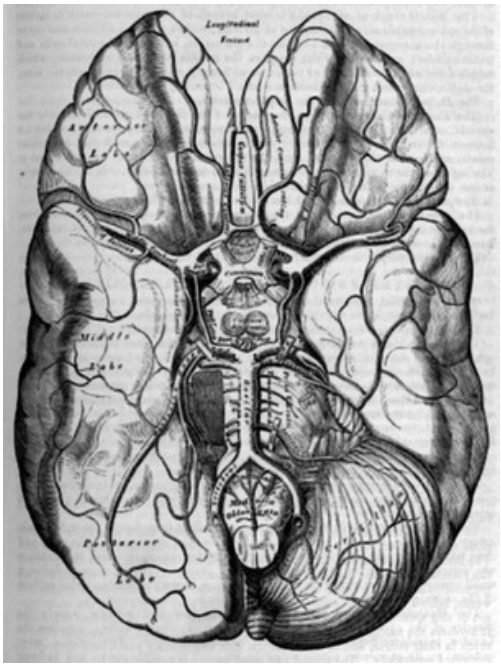

Figure 2. Basal view of the brain with the arterial circle. The right half of the cerebellum and pons have been removed (Gray, 1858 - p 337 [Figure 196]). Depicted by Henry Vandyke Carter.[39]

COMMENTS

The description of arteries at the base of the human brain constituted a focus of interest since the restoration of human dissection. A number of descriptions and illustrations of the arteries that form a circle or polygon of Willis, with variable completeness, were performed by many outstanding pre-Willisian authors, among which the names of Giulio Casserio (1627), Johann

Vesling (1647), and Johann Jakob Wepfer (1658) should be highlighted, culminating with the exemplary work of Thomas Willis (1664), which earned him the eponym that remains in use in the present days. Such initial research lasted over three centuries. Despite a complete description and depiction of the arterial components of the circle, at the end of this period, their naming lagged behind[1].

After Willis, a large number of renowned anatomists, the post-Willisian, studied this formation further. This period begun with a poor contribution of Isbrand van Diemerbroeck (1672). Next appeared authors who provided names that became ephemeral, followed by those who presented designations that would remain permanently, appearing in a gradual manner. Among the latter must be initially cited Joseph Lieutaud (1742), and Albrecht von Haller (1756). They were followed by Xavier Bichat with his posthumous work (1803), where the definitive basis of the nomenclature appeared, and the definitive names were established by Jean Cruveilhier (1834). However, their work was incomplete, as they did not provide an illustration of their findings. This period was closed with Henry Gray's book (1858), who not only utilized the already given definitive names of the components, but also provided a correct illustration of the arterial circle, consolidating the knowledge on the subject. This period spanned almost two centuries of research.

CONCLUSION

The study of the arteries at the base of the human brain begun with the reintroduction of human dissections, in the beginning of the 14th century. The first period was characterized by the achievement of the structural definition of the component arteries, with the recognition of an arterial circle or polygon – the 'circle of Willis', in the 17th century. A second period comprised the nomenclature of the arterial components of this circle, which gradually came to be established in the middle of the 19th century. The total duration of this work lasted more than a half millennium, requiring a large number of renowned anatomists to be finally completed.

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