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

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

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ABSTRACT

The description of arteries at the base of the human brain forming an 'arterial circle', named after Thomas Willis, has had a long history after the restoration of human dissection, partly due to the studies of many outstanding anatomists that preceded Willis. He provided, with the collaboration of Richard Lower and Christopher Wren, the first incontestable complete description, as recognized nowadays, accompanied by a superb illustration. Additionally, he presented an explanation for its meaning, indicating for the first time the functional significance of this structure, in health and disease. However, it should be recognized that the initial studies of the arteries of the base of the human brain by Willis' predecessors, as well as those from ancient times, despite their fragmentary descriptions, were certainly pivotal in paving the way for further and more detailed knowledge of this vascular formation.

Keywords: Willis, arterial circle, plexiform net

RESUMO

A descrição das artérias da base do cérebro humano, formando um 'círculo arterial', designado com o nome de Thomas Willis, tem uma longa história após o restauro de dissecções humanas, em parte devido aos estudos de muitos anatomistas de renome que precederam Willis. Ele proveu, com a colaboração de Richard Lower e Christopher Wren, a primeira descrição completa e incontestável, assim como a reconhecida atualmente, acompanhada por uma ilustração soberba. Adicionalmente, apresentou uma explicação quanto ao seu significado, indicando pela primeira vez a importância funcional dessa estrutura, na saúde e na doença. Entretanto, deve ser reconhecido que os estudos iniciais das artérias da base do cérebro humano pelos predecessores de Willis, assim como os de tempos antigos, apesar de suas descrições fragmentárias, certamente foram fulcrais na pavimentação do caminho para o conhecimento mais avançado e detalhado dessa formação vascular.

Palavras-chave: Willis, círculo arterial, rede plexiforme

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INTRODUCTION

The arterial circle (or polygon) at the base of the brain, the circle of Willis, is formed by anastomoses between the carotid and vertebrobasilar systems, surrounding basal structure of the brain (optic chiasm, infundibulum, mammillary bodies), in the suprasellar cistern. The arteries that form this structure comprise the internal carotid artery (ICA), the initial horizontal segments of the anterior cerebral arteries (ACA) (A1), the initial segment of the posterior cerebral arteries (PCA) (P1), and the tip of the basilar artery, beside the anterior communicating artery (ACoA), and the posterior communicating arteries (PCoA), which form the anastomotic link between the right-left, and anterior-posterior circulations[1, 2, 3] (Figure 1).

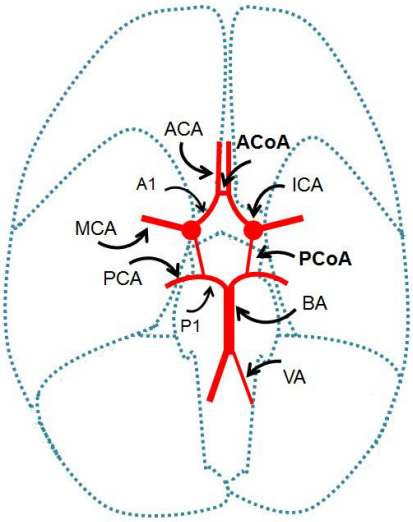

Figure 1. Simplified schema of the brain with projection of the arterial circle (of Willis) (based on Gray's "Anatomy of the Human Body")[2].

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

Here the Willis' study will be revisited, emphasizing his contribution, and giving consideration to those who preceded him

THE ARTERIAL CIRCLE AS DESCRIBED BY WILLIS

The English physician Thomas Willis (1621-1675) studied and dissected the nervous system of man and of varied animals, with the collaboration of the physicians Richard Lower, Thomas Millington, and Christopher Wren, which resulted in the book "Anatomy of the Brain and the Description and Use of the Nerves" (*Cerebri Anatome cui Accessit Nervorvm Descriptio et Usus*) published by Willis (1664). There (Chapter I) he describes the base of the brain (the optic nerves [optic chiasma], the funnel [infundibulum], and the two glands behind the funnel [mammillary bodies]), and also the presence of four arteries two carotids (*carotides*) and two vertebrals (*vertebrales*): the carotid arteries ascend at each side of the infundibulum, and divide in an anterior and a posterior branch, the anterior branches [ACA] [A1] approach and join to each other [ACoA], while the "...posterior branches [PCoA] unite with branches [PCA] of the [fused] vertebrals (previously coalesced into one trunk) [BA]..." (...*rami posteriores ita conjuncti, cum ramis vertebralibus (priùs in unum truncum coalescentibus) uniuntur*...) This dissected basal view of the brain and its vasculature were depicted by Wren, physician and architect, and excellent drawing-artist[4, 5]. The circle or polygon formed by these arteries was later was named after Willis (Figure 2).

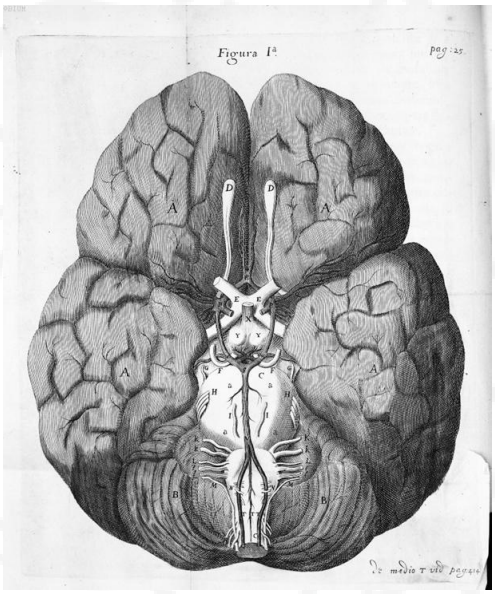

Figure 2. Willis' basal view of the brain with the arterial circle, depicted by Christopher Wren, from the *Cerebri Anatome* (1664) (Chapter 1 - Figure I)[5]

PP=trunks of the carotid arteries [ICA] dividing in anterior and posterior branches, R= union [ACoA] of the anterior branches [ACA] [A1] of the carotid arteries, posterior unnamed branches [PCoA] of the carotids united with the branches [PCA] of the common vertebral trunk [BA]

Willis described further the intracranial vasculature (Chapter VIII), the carotids and vertebral arteries. He confirmed the inexistence in man of the retiform plexus (*rete mirabile*), as already verified by Vesalius (as will be seen below), a network of small arteries in the base of the brain of artiodactyls (e.g., ox), resulting from branching of the internal carotid arteries[5]. This network was initially described by the Alexandrian anatomist Herophilus of Chalcedon (ca 335-ca 280 BC), who dissected human corpses, and heads of animals (oxen, sheep), and identified (certainly in the latter) a vascular net formed at the base of the brain from the (internal) carotid arteries, and used the term 'net-like plexus' (*plegma diktyoeides*) to designate this structure[6]. Later, this finding was acknowledged, and detailed by Claudius Galenus (129-ca 216 AD), who dissected animals of varied kinds only. He described the net at the base of the brain, formed by very small arteries originating from an artery entering into the cranium coming from the neck [ICA], located bilaterally in anterior and posterior positions, then fusing in only one artery on each side, and named the formation as 'retiform plexus' (*plexus*

retiformes) (*rete mirabile*). The notion that the retiform plexus was also present in the human brain was maintained by Galenus' followers, and by the pre-Willisian authors, as reviewed below, for more than one and a half millennium[7,8,9].

Willis, beside establishing the anatomical structure of the circle, also made the first attempt to assign a function to this formation. This was accomplished by dye injections in human corpses and experimental animals, a technique developed by Wren and implemented by him and by Lower, founding the basis for the discovery of the flow of blood in the cerebral arteries[4, 10, 11, 12]. He also conjectured, based on clinical-pathological cases, that blockage of one or more of the four main cerebral arteries would not lead to apoplexy, one being sufficient to supply the brain, questioning arguments of the "famous Wepferus" (Wepfer), in the following way (excerpts from translation of Samuel Pordage of Willis' "The Soul of Brutes" [1683]): "...in the first place, though we grant that the flowing in of the blood, may be sometimes denyed to the brain, yet we do not believe that it only happens after the aforesaid ways, nor that, for that reason, the apoplexy doth arise. We have elsewhere shewed that the cephalick arteries, viz., the carotides, and the vertebrals do so communicate one with another, and all of them in several places, are so ingraffed one in another mutually, that if it happen, that many of them should be stopped or pressed together at once, yet the blood being admitted to the head, by the passage of one artery only, either the carotid or the vertebral, it would presently pass thorow all those parts both exterior and interior: which indeed we have sufficiently proved by an experiment, for that ink being squirted in the trunk of one vessel, quickly filled all the sanguiferous passages, and every where stained the brain it self...". He continues reasoning: "...I once opened the dead carcase of one wasted away, in which the right arteries, both the carotid and the vertebral, within the skull, were become bony and impervious, and did shut forth the blood from that side, notwithstanding the sick person was not troubled with the astonishing disease [apoplexy]..." (1672)[13].

The mention of Willis' *Cerebri Anatom*e and his other books appeared in *Bibliotheca Anatomica* (1774-1777), published by Albrecht von Haller, where he quoted "a circle that is called of Willis" (*circulum qui dicitur Willisii*), in volume I (p 476), and the designation "circle of Willis" (*circulus Willisii*), in volume II (p 594), as a citation of the Dutch physician Andrea Bonn, who referred to the arterial circle in his doctorate thesis "Continuations of the Membranes" (*Continuationibus Membranarum*) (1763) as follows: "...Therefore, it is clear that the junction of the carotid and vertebral arteries form the circle of Willis..." (*Patet ergo concursus arteriarum carotidum & vertebralium, ubi circulum Willisii conftituunt...*)[12, 14, 15, 16, 17]. The citations in the *Bibliotheca Anatomica*, the most comprehensive compilation of anatomical works and authors produced in the 18th century, made Willis' work well known and the circle definitely accepted[10, 11, 16, 17].

THE DESCRIPTIONS THAT PRECEDED WILLIS'

Descriptions of arterial anastomosis at the base of the brain existed before Willis, but his description represents a significant improvement on former versions, and as noted above, he made the first attempt to assign a function to this formation[12]. Some outstanding pre-Willisian anatomists must be mentioned, among them Mondino de Luzzi, Jacopo Berengario da Carpi, Andreas Vesalius, Realdo Colombo, Gabriele Falloppio, Giulio Casserio, Johann Vesling, Johann Jakob Wepfer, whose books contained descriptions, and some also illustrations, of the arteries at the base of the brain, with varied details, several insisting on the existence of the retiform plexus in the human brain[12, 18], as follows.

Mondino de Luzzi

Mondino de Luzzi (Mundinus) (1270-1326), Italian physician and anatomist, credited for performing the first human dissections after the prohibition period with anatomical purpose, authored the book "Anotomy" (*Anothomia*) (1316), where he describes the visualization, lifting gradually the brain, the base and its structures, the optic nerves (*nervus opticus*), infundibulum (l*acuna*), and mammillary bodies (*carunculae*), surrounded by very fine arteries forming a net, the retiform plexus (rete mirabile), branches of the 'apoplectic artery' (*arteriarum appoplecticarum*) [ICA]. He cites repeatedly Aristoteles and Galenus[12, 19].

Berengario da Carpi

Jacopo Berengario da Carpi (ca 1460-ca 1530), Italian physician, author of the book "Short Introduction, Clear and Rich, of the Human Body Anatomy" (*Isagoge breves, Perlucidae ac Uberrimae, in Anatomiam Humani Corporis*) (1522, 1523), where he frequently cites Mondino, whose *Anathomia* he has commented previously, describes the base of the brain (infundibulum [Mondinus's *lacuna*], mammillary bodies, optic nerves), and two ascending arteries [ICA] near the basilar bone, which he acknowledges that according to some authors, divide in many very fine branches forming a network (*rete mirabile*), which existence he denies: "However I never saw this net" (*Istud tamem rete ego numque vidi*)[8, 20].

Andreas Vesalius

Andreas Vesalius (Andries van Wesel) (1514-1564), Dutch anatomist and physician, performed dissections on human corpses, and of animals (oxen, sheep), and published the admirable book "On the Structure of the Human Body" (*De Humani Corporis Fabrica Libri Septem*) (1543), illustrated by Jan Stephan van Calcar (disciple of Tiziano), and based on human dissections. There he describes in Book III the 'soporal arteries' (*arteriae soporalis*) [*sopor*=stupor], called 'carotids' in Greek (*karotis* [*καρωτίς*]), which ingresses into the cranium, moving to the

base of the brain, and the unnamed arteries [VA] that enter the cranium after passing through the transversal processes of the cervical vertebrae. The Figure 14 displays the venous and arterial circulation of the head. There are represented the 'soporal arteries', and unnamed arteries ascending through the transversal processes of the vertebrae and penetrating into the cranium [VA]. Further, he describes the large lateral arteries [common carotid artery] that enter the cranium, and after giving a branch that accompanies de optic nerve [ophthalmic arteries], emerge at the sides of the pituitary gland [ICA], dividing in two branches that ramifies and are distributed to the nearby brain structures (pp 496-501). Book VII contains the figures that illustrate poorly the arteries of the base of the brain. There, displayed the interior of the basis of the cranium (Figure 13 [p 768]), are the 'soporal arteries' [ICA] flanking the sella turcica, and parts of the [poorly preserved] brainstem, and the pituitary gland (Figure 14 [p 769]), with a segment of an artery [ICA], and an unnamed artery at the level of the pons [BA]. Next, in another illustration (Figure 15 [p 770]), is displayed a snip of the infundibulum, and on each side, segments of arteries [ICA], and a drawing of the same structures in the illustration that follows (Figure 16 [p 771]). He denies the existence of the retiform plexus, which Galenus has described, in the human brain (p 796). He cites repeatedly Galenus, frequently with disapprovals[21,22] (Figure 3).

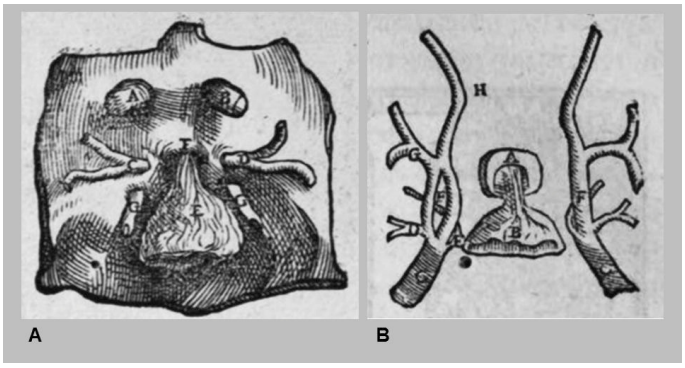

Figure 3. Vesalius' basal view (snip) of the brain with arteries of the circle, depicted by Jan Stephan van Calcar (Book VII)[21].

A. Figure 15. A+B=visual [optic] nerves, C+D=lateral arteries [ICA], E=infundibulum, GG=second pair [oculomotor]
B. Figure 16. A=pituitary gland, B=funnel [tuber cinereum], CC=parts of the arteries [ICA] that enter into the cranium through a obliquely carved duct [in the bone], FF=arteries [ICA], G=segment of the left artery, part directed to the base of the brain, and part to the ventricle, H=branch of the left artery, which leaves the cranium through the orifice of the second nerve [ophthalmic artery]

Realdo Colombo

Matteo Realdo Colombo (Columbus) (ca 1515-1559), Italian anatomist, in Book VII (*De corde et arteriis*) of his "On the subject of Anatomy" (*De re Anatomica*) (1559), he describes the 'carotid arteries' (*carotid arteriae*) (*καρωτδας*) (*soporarias*) that ingress into the cranium, and also two 'not-soporal' (*nõ à soporariis*) [not-carotid] arteries that ascend from the cervical spine [VA], entering in the posterior part of the cranium between the first vertebra and the occipital bone, and after joining with the opposite constitute one trunk [BA], which divides in two [PCA]. He writes also about the plexiform net, apparently in a doubtful way: "...that it is not surprising that the retiform plexus (*rete mirabile*), formed by the carotid arteries, so much chanted by the ancient anatomists, which I do not know by what means do they mock...". Next, in Book VIII, he writes about the brain, and mentions at its base the plexiform net, without further anatomical details[23].

Gabriele Falloppio

Gabriele Falloppio (Falloppius) (1523-1562), Italian anatomist, described in his "Anatomical observations" (*Observationes anatomicae*) (1561) the arteries destined to the brain: "...The first artery [VA], after traversing the cervical spine... enter the cranial cavity, and under the origin of the medulla [oblongata] joins with its partner of the opposite side, making one artery [BA], which creeps under the middle of the brain until the region of the sella [sella turcica]...there it divides in two branches [PCA]...they divide in numerous branches...". Then, he continues: "...the 'large soporal artery' (*arteria à soporaria magna*) (karotis [*καρωτίς*]) [common carotid artery] ... divides...one branch [ICA] progresses into the cranial cavity, divides to form the rete in animals, not marked in man, but only a shadow of its image...enters under the base of the brain...and divides in two branches, the interior [ACA] joins with the opposite one [ACoA], making one artery from two, which divides in numerous small arteries (*arteriolas*)...". Then: "...the external branch likewise produces innumerable small arteries (*arterioles*), some of which join [PCoA?] with the small arteries...with those hat first reached the base of the brain [PCA] (as was stated)..."[12, 24, 25]. The lack of an illustration makes an accurate interpretation of what is described difficult.

Giulio Casserio

Giulio Cesare Casserio (Casserius) (Placentinus) (1552-1616), Italian anatomista, provided the first illustrations of the components of the arterial circle, which appeared in the compilation of the "Anatomical Plates" (*Tabulae Anatomicae*) [1613], many drawn by Odoardo Fialetti (a pupil of Tintoretto). These illustrations were not published during Casserio's lifetime. Later they were incorporated into *De Humani Corporis Fabrica Libri Decem* of Adrainus Spigelius (van den Spiegel) (1578-1625), and with his passing, was edited and published by Daniel Rindfleisch (Bucretius) (1627). The Book X of Casserio's *Tabulae* contains two plates with figures that display the arteries of the base of the brain. The first figure (Plate IX – Fig. II) shows the posterior part of the circle, with the vertebral arteries (ZZ) joining to form a single trunk (c-d segment) [BA], which bifurcates (ee) [PCA], the resulting branches being connected (point a) [PCoA] to the carotid arteries (GG) [ICA]. The right carotid originates a medial branch (H) [ACA], which ends under the optic nerve, and on the other side a similar branch (H) courses lateralward, plunging under the temporal lobe, not existing a left anterior artery, nor an anterior junction. The next figure (Plate X) shows the ST segment [BA] bifurcating in two

terminal branches [PCA], the left connecting directly with the carotid artery (K) [PCoA], while the right one coursing lateralward; a thin connecting artery may be seen [not clear] coursing to the right carotid; anteriorly, each carotid artery (KK) originate an anterior branch (bb) [A1] which join at C [ACoA], both continuing forward after the junction; additionally is displayed LL=branches of the carotid forming the retiform plexus [rete mirabile][12,24,26,27] (Figure 4).

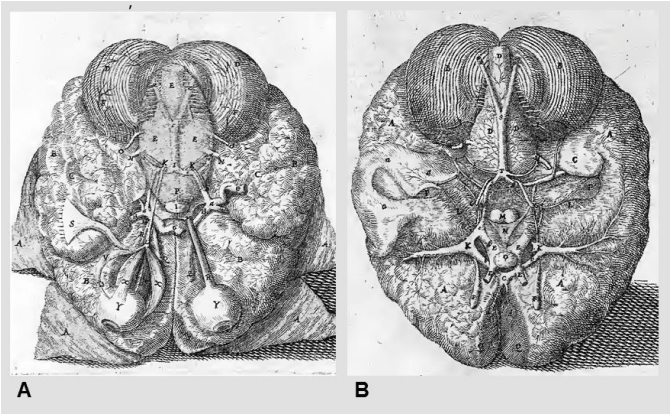

Figure 4. Casserio's basal view of the brain with the arterial circle, depicted by Odoardo Fialetti (Book X)[24 26].

A. Plate IX. Figure II: CC=vertebral arteries, that join, and form a trunk [c-d] [BA], which divides in two branches [PCA], GG=internal carotid arteries [ICA], originating the retiform plexus [rete mirabile], and dividing in a medial branch H [ACA] [A1] at the right side, ending under the optic nerve, and a lateral branch H at the left side, plunging under the temporal lobe [MCA], no anterior branch is seen at the left side, neither an anterior communication, two arteries connecting the ramifications [PCA] of the common vertebral trunk, and the carotid arteries, an unnamed posterior communication [PCoA] may be seen

B. Plate X: KK=trunks of the carotid arteries [ICA], dividing in an medial [anterior] branch [ACA], C=junction of the former [ACoA] and dd=continuing forward, RR=cervical arteries, by others, and named by Spigelio as vertebral arteries, S=junction of the former, forming a trunk [S-T] [BA], which at T=divides in two branches=gg, the right branch course forwards and unites with the carotid artery [PCoA], while the left branch course laterally, and a posterior communication is not seen, LL=branches of the carotid forming the retiform plexus [rete mirabile]

Johann Vesling

Johann Vesling (1598-1649), German anatomista, displayed a complete arterial circle in his "Anatomical Collection" (*Syntagma Anatomicum*) (Chapter XIV - Plate III - Figure III). There is shown the internal carotid artery (*arteria carotidis ramus maior, interior*) (CC) [ICA], which divides into 2 branches, the anterior [ACA] on each side coursing very closely, with a indistinct anterior anastomosis [ACoA]; the apparent posterior branches are in direct communication [PCoA] with the branches resultant from the division of the common trunk [BA] of the vertebral arteries (OO), appearing as a direct continuation of the redivided common trunk, while the posterior arteries are missing; he also describes "very small branches that forms what some designate plexiform net (*rete mirabile*)"(=PPPP)[12, 28](Figure 5).

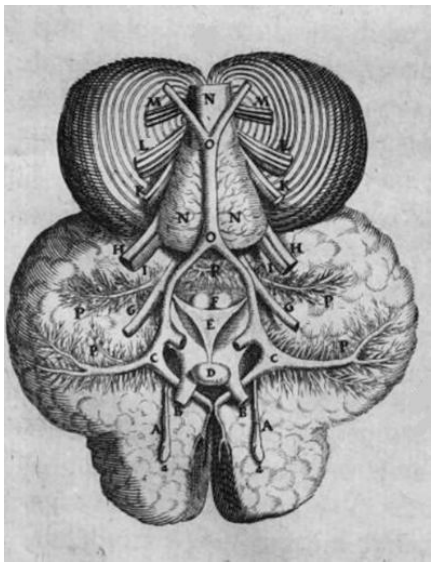

Figure 5. Vesling's basal view of the brain with the arterial circle (Chapter XIV)[28]

Plate III - Figure III: OO=common trunk of the vertebral arteries [BA], which divides in two after the union, each branch uniting directly with the apparent posterior branches of the CC=carotid arteries [ICA], , the anterior branches, unnamed, runn very closely, with an indistinct junction [ACoA], PPPP=very small branches that form what some designate as plexiform net (*rete mirabile*)

Johann Jakob Wepfer

Johann Jakob Wepfer (1620-1695), Swiss physician, in his "Anatomical Observations from corpses of those who suffered apoplexy" (*Observationes anatomicae ex cadaveribus eorum quos sustulit apoplexia*) (1658), describes the complete circle, as follows: "...regarding the carotid arteries (*arterias carotides*), after leaving the bony channel continue winding and curving...to the sides of the sella and the pituitary gland...after perforating the dura matter it [ICA] divides in an anterior and a posterior branch...the anterior branch [ACA]...proceed towards the crista galli... where the right branch [A1] is joined to the left [ACoA]... further again separated...next the posterior branch...after a short course, becomes connected with the vertebral artery [BA] again divided [PCA] establishing a continuous duct (*continuusque ductus*) [PCoA]... regarding the vertebral arteries (*arterias vertebrales*)...they emerge... proceed to the sides of the medulla oblongata...the right and left branches unite constituting one only channel (*unicumque canalem constituent*) [BA] remaining united over the whole extent of the medulla ...later the trunk divides in two branches [PCA], and connects with the posterior branch of the carotid artery [PCoA], as already mentioned... "; he questioned the rete (denied?). He cites frequenly Fallopio, Vesling, and other authors[12 29].

COMMENTS

The description of arteries at the base of the human brain forming an 'arterial circle' has had a long history after the restoration of human dissection, largely due to the studies of many outstanding anatomists that preceded Willis, such as Colombo, Falloppio, Casserio, Vesling, Wepfer, each one making contributions that culminated with Willis' description. Three of the many

authors must be highlighted – Vesling (1627), who presented a complete, albeit atypical circle, Casserio (1647), who presented two excellent, although incomplete illustrations of the circle, which however, if taken together, allow the understanding of the complete circle, and Wepfer (1658), who gave a detailed and complete description of the circle, but unfortunately without providing an illustration[12, 18, 30].

Willis, with the collaboration of Lower and Wren, provided a complete description, with all components of the circle, illustrated by an excellent artist (1664), as recognized nowadays. Additionally, as noted, provided an explanation for its meaning, indicating for the first time the functional significance of this structure, in health and disease[5, 13].

With the description and illustration of Willis (and collaborators) of the arterial circle, the knowledge of the formation was completed. However, the names of the component segments of the circle, except of the carotids and vertebrals, were only ascribed by future authors.

The initial studies of the arteries of the base of the human brain by Willis' predecessors, with the reestablishment of human dissection (e.g., Mondino, Berengario da Carpi, Vesalius), should be recognized, despite their fragmentary descriptions, were certainly helpful toward further and more detailed studies[30].

Other studies from ancient times should not be forgotten, as those of Aristoteles and Claudius Galenus, who dissected animals only, some complemented with experimental investigations, preceding for more than one and a half millennium the modern ones, and that were also pivotal in paving the way for the forthcoming anatomists[30,31].

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