



Anatomy of the optic nerve based on cadaveric dissections and its neurosurgical approaches: a comprehensive review

Ramiro López-Elizalde^{1,✉}, Marisol Godínez-Rubí², Yazmín Lemus-Rodríguez³, Elizabeth Mercado-Rojas⁴, Tania Sánchez-Delgadillo³, David Sánchez-Delgadillo³, Álvaro Campero⁵, Richard Gonzalo Párraga⁶

¹ Health Regulatory Directorate, Instituto de Seguridad y Servicios Sociales de los Trabajadores del Estado, City of Mexico, Mexico

Avenida las Palmas S/N, Fraccionamiento las Palmas, 22106 Tijuana, B.C., Mexico

² Laboratorio de Investigación en Patología, Departamento de Microbiología y Patología, Centro Universitario de Ciencias de la Salud, Universidad de Guadalajara, Guadalajara, Jalisco, Mexico
Sierra Mojada 950, Independencia Oriente, 44340 Guadalajara, Jalisco, Mexico

³ Servicio de Neurocirugía, Hospital General Dr. Valentín Gómez Farías, ISSSTE, Guadalajara, Jalisco, Mexico
Av. Soledad Orozco 603, 45100 Zapopan, Jalisco, Mexico

⁴ Servicio de Neurocirugía, OPD Hospital Civil Juan I. Menchaca, Guadalajara, Jalisco, Mexico
Salvador de Quevedo y Zubieta No. 750 S L, C P 44340, Guadalajara, Jalisco, Mexico

⁵ Servicio de Neurocirugía, Hospital Padilla, Tucumán, Argentina
Juan Bautista Alberdi 550, T4000 San Miguel de Tucumán, Tucumán, Argentina

⁶ Instituto de Neurocirugía de Bolivia (INEB), Cochabamba, Bolivia
Av. Papa Paulo N 761, Cochabamba, Bolivia

Abstract

Vision is a complex sense that is widely represented in the cortex and involves multiple pathways that can be affected by conditions amenable to surgical treatment. From a neurosurgical point of view, the treatment of major lesions affecting the optic nerve, such as tumours, intracranial hypertension, trauma and aneurysms, can be approached depending on the segment to be worked on and the surrounding structures to be manipulated. Therefore, surgical manipulation of the visual pathway requires a detailed knowledge of functional neuroanatomy. The aim of this review is to present the functional and microsurgical anatomy of the second cranial nerve, through illustrations and cadaveric dissections, to support the choice of the best surgical approach and avoid iatrogenic injuries. For this purpose, a literature search was performed using the PubMed database. Additionally, cadaveric dissections were performed on adult cadaver heads fixed with formaldehyde and injected with coloured silicone.

Keywords: optic nerve; visual pathway; cranial nerves; neuroanatomy; neurosurgical procedures

MeSH terms:

OPTIC NERVE – ANATOMY & HISTOLOGY

OPTIC NERVE – SURGERY

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CONTACT INFORMATION:

Ramiro López-Elizalde, Health Regulatory Directorate, Instituto de Seguridad y Servicios Sociales de los Trabajadores del Estado

Address: Ave. San Fernando 547, 8th floor, Tlalpan, C.P. 14050, Ciudad de México, México.

Tel.: +52 555 1409617

E-mail: ramirolopezelizalde@hotmail.com

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Комплексный обзор анатомии зрительного нерва и нейрохирургических доступов на основе кадаверных срезов

**Р. Лопес-Элизальде^{1,✉}, М. Годинес-Руби², Я. Лемус-Родригес³, Э. Меркадо-Рохас⁴,
Т. Санчес-Дельгадильо³, Д. Санчес-Дельгадильо³, А. Камперо⁵, Р. Г. Паррага⁶**

¹ *Медицинское управление, Институт социального обеспечения и услуг*

для государственных служащих, г. Мехико, Мексика

Авеню лас Пальмас S/N, Фракционамента лас Пальмас, 22106 Тихуана, Б.К., Мексика

² *Научно-исследовательская лаборатория патологии, кафедра микробиологии и патологии,
Университетский центр наук о здоровье, Университет Гвадалахары, Гвадалахара, Халиско, Мексика*

Сьерра Мохата 950, Индепенсия Ориенте, 44340 Гвадалахара, Халиско, Мексика

³ *Нейрохирургическая служба, Главный госпиталь доктора Валентина Гомеса Фарриаса, ISSSTE,
Гвадалахара, Халиско, Мексика*

Авеню Соледад Ороско 603, 45100 Сапопан, Халиско, Мексика

⁴ *Нейрохирургическая служба, гражданская больница OPD Хуана И. Менчака, Гвадалахара,
Халиско, Мексика*

Сальвадор Кеведо и Зубиета 750, Индепенсия Ориенте, 44340 Гвадалахара, Халиско, Мексика

⁵ *Отделение нейрохирургии, госпиталь Падилья, Тукуман, Аргентина*

Хуан Баутиста Альберди 550, T4000 Сан-Мигель-де-Тукуман, Тукуман, Аргентина

⁶ *Институт нейрохирургии Боливии (INEB), Кочабамба, Боливия*

Авеню Папа Паоло N 761, Кочабамба, Боливия

Аннотация

Зрение – это сложный орган чувств, широко представленный в коре головного мозга и включающий в себя множество трактов, которые могут быть затронуты заболеваниями, поддающимися хирургическому лечению. В нейрохирургии лечение основных поражений, влияющих на зрительный нерв, таких как опухоли, внутричерепная гипертензия, травмы и аневризмы, можно рассматривать с точки зрения сегмента, на котором ведется оперативное вмешательство, и окружающих структур, подвергаемых хирургическим манипуляциям. Для выполнения хирургических манипуляций на зрительных путях требуется детальное понимание функциональной нейроанатомии. Цель данной работы – продемонстрировать функциональную и микрохирургическую анатомию зрительного нерва с помощью иллюстраций и кадаверных срезов, что необходимо для выбора оптимального хирургического доступа и исключения ятрогенных повреждений. Для достижения поставленной цели был подготовлен обзор литературы с использованием базы данных PubMed. Кроме того, была выполнена кадаверная диссекция препаратов голов взрослых людей, фиксированных формальдегидом с инъекцией сосудов цветным силиконом.

Ключевые слова: зрительный нерв; зрительный тракт; черепные нервы; нейроанатомия; нейрохирургические процедуры

Рубрики MeSH:

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КОНТАКТНАЯ ИНФОРМАЦИЯ:

Рамиро Лопес-Элизальде, Медицинское отделение, Институт безопасности и социальных услуг для государственных работников, г. Мехико, Мексика.

Адрес: Авеню Сан Фернандо 547, 8 этаж, Тлалпан, С.Р. 14050, Мехико, Мексика.

Тел.: +52 555 1409617

E-mail: ramirolopezelizalde@hotmail.com

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HIGHLIGHTS	КЛЮЧЕВЫЕ ПОЛОЖЕНИЯ
The optic nerve is an extension of the telencephalon in the form of tracts.	Зрительный нерв в виде трактов является продолжением конечного мозга.
Iatrogenic optic nerve damage in neurosurgical procedures is avoidable with accurate knowledge of neuroanatomy.	Глубокое знание анатомии позволяет избежать риска ятрогенного повреждения зрительного нерва при нейрохирургических операциях.
Damage of the neurovascular structures surrounding the optic nerve can result in significant visual loss.	Повреждение нейрососудистых структур, окружающих зрительный нерв, может привести к значительной потере зрения.
Cadaveric dissections are an invaluable tool for gaining knowledge of neurosurgical anatomy.	Кадаверная диссекция является бесценным инструментом для изучения нейрохирургической анатомии.
Ignorance of the anatomical variants of the optic nerve can lead to errors during the neurosurgical procedure.	Незнание анатомических вариантов зрительного нерва может привести к ошибкам во время нейрохирургической операции.
The choice of neurosurgical approach depends on the segment of the optic nerve to be approached.	Выбор нейрохирургического доступа зависит от того, к какому сегменту зрительного нерва будет осуществляться доступ.

The vision is a complex sense that has a broad representation in the cortex. The optic nerve, like the olfactory nerve, is not a true peripheral nerve but an extension of the telencephalon in the form of tracts [1, 2]. From a neurosurgical perspective, the leading lesions that affect the optic nerve and are susceptible to surgical treatment are tumours, intracranial hypertension, traumatic brain injury, hematomas and aneurysms [3]. A detailed knowledge of the microsurgical anatomy of this nerve and neighbouring structures in cadaveric models contributes to the success of surgical treatments and avoids post-operative visual deficits, by minimizing the risk of a direct surgical injury [4]. Below we present a brief review of the functional anatomy of the visual pathway, and a description of the surgical anatomy of the optic nerve, based on cadaveric dissections and histologic sections.

FUNCTIONAL ANATOMY OF THE OPTICAL PATHWAY

Unlike other sensitive neural pathways such as smell, touch or hearing, which use a single neuronal relay to send the signal directly to the central structures, the visual path requires two further steps to connect to the cortex (three synaptic relays) [5]. The first three neurons are found in the retina, the fourth relay is at the lateral geniculate body and projects to the primary visual cortex (calcarine cortex) in the occipital lobe. In both, the lateral geniculate body and the calcarine cortex, retinal distribution of the stimuli is preserved with high accuracy, creating a retinotopic map that allows the visual information of both eyes to be integrated [6].

Retina

The retina is a light-sensitive layered tissue that coats the eyeball-inner-posterior surface. It originates from the

embryonic diencephalon and contains different kinds of neurons: photoreceptors (cones and rods), ganglion, bipolar, amacrine and horizontal neurons. It also contains neuroglia, such as Müller's (radial glial) cells, astrocytes, and microglia. Müller's cells contribute to the formation of inner and outer retinal limiting barriers, and, during embryonic development, they guide the cellular stratification of the retina [7]. Astrocytes provide metabolic support to the other retinal components, regulate blood flow in the optic nerve and are major contributors to the blood-retinal barrier. Microglia participate in the local innate immune response [8].

Three of the retinal layers are made up of somas from retinal cells (ganglion cell layer, inner nuclear layer, and outer nuclear layer) and two layers are made up of the synapses between these cells (inner and outer plexiform layers) [7]. Light passes through the five

inner layers to reach and stimulate the photoreceptors (outer nuclear layer). The average human retina is comprised of 92 million rods and 4.6 million cones. Rods are responsible for dim-light vision because they can detect single-photons [9], while cones are for colour vision due to a better sensitivity to red, green and blue colours [7]. Pigmentary epithelium and choroid are beyond the cytoplasmic projections of photoreceptors (Fig. 1) [5].

The retina varies in structure in different regions. The macula is a specialized area, 5-6mm in diameter, located on the temporal side. In this area, the stratum of ganglion cells has several layers of thickness. The fovea, (within the macula,) a small depression in the surface of approximately 1–1.5 mm, specializes in high-definition visual acuity. While rods are more abundant in the periphery of the retina, cones are particularly plentiful in

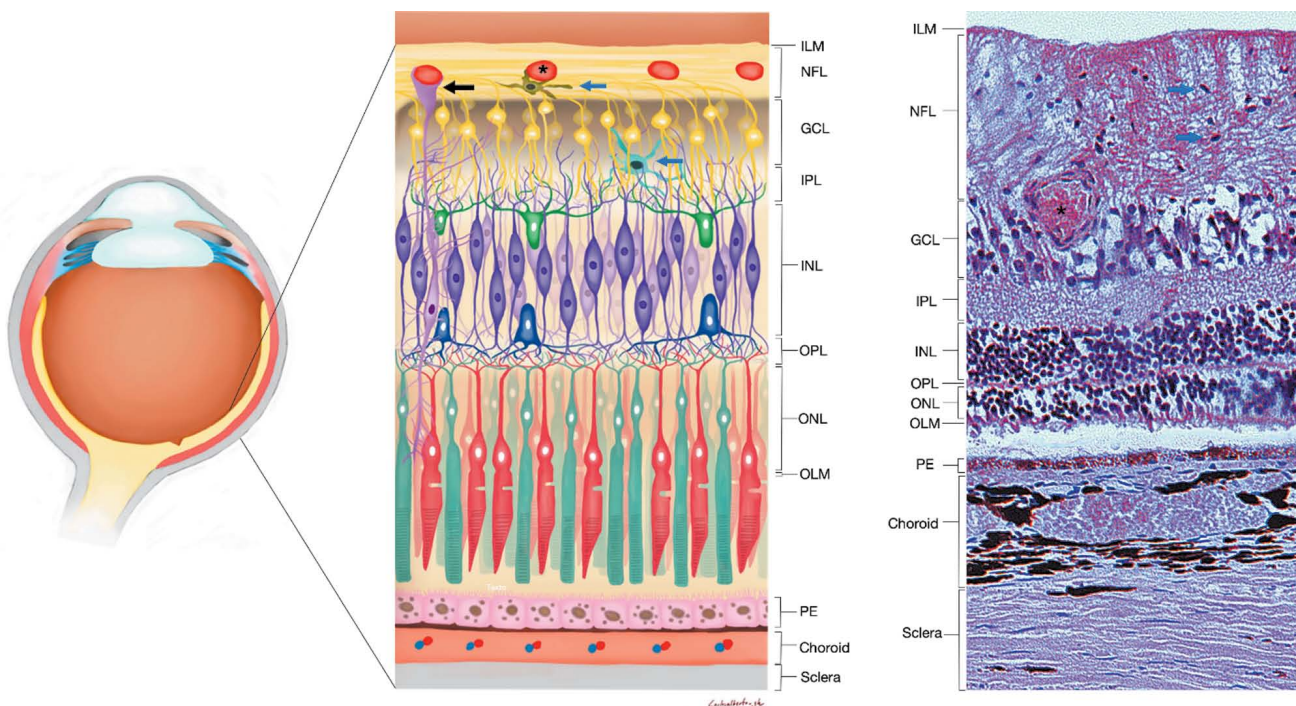


FIG. 1. Types of neurons and signalling cells in the retina.

Schematic illustration of the eyeball as well as neurons, glia and other structural elements on each layer of the retina, seen on the right on a hematoxylin and eosin-stained section. In the schematic view, a Müller's glial cell is labelled with a black arrow. Other glial cells (astrocytes and microglia, blue arrows) are mainly localized in the outermost layers; their nuclei are easily identified in the histological section. A capillary (*) can be seen in the transition between the ganglion cell layer and their axons.

РИС. 1. Типы нейронов и сигнальных клеток в сетчатке глаза.

Схематическое изображение глазного яблока, а также нейронов, глии и других структурных элементов на каждом слое сетчатки – справа на срезе, окрашенном гематоксилином и эозином. На схематическом изображении глиальная клетка Мюллера обозначена черной стрелкой. Другие глиальные клетки (астроциты и микроглия – синие стрелки) локализованы в основном в наружных слоях; их ядра легко идентифицируются на гистологическом срезе. Капилляр (*) можно увидеть в переходе между слоем ганглиозных клеток и их аксонами.

Note: GCL – ganglion cell layer; ILM – internal limiting membrane; INL – inner nuclear layer; IPL – inner plexiform layer; NFL – nerve fibre layer; OLM – outer limiting membrane; ONL – outer nuclear layer; OPL – outer plexiform layer; PE – pigment epithelium.

Примечание: GCL (ganglion cell layer) – слой ганглиозных клеток; ILM (internal limiting membrane) – внутренняя ограничительная мембрана; INL (inner nuclear layer) – внутренний ядерный (зернистый) слой; IPL (inner plexiform layer) – внутренний плексиформный слой; NFL (nerve fibre layer) – слой нервных волокон; OLM (outer limiting membrane) – наружная ограничительная мембрана; ONL (outer nuclear layer) – наружный ядерный слой; OPL (outer plexiform layer) – наружный плексиформный слой; PE (pigment epithelium) – пигментный эпителий.

the macula, specifically in the fovea, which contributes to increased visual acuity [10].

Optic nerve and chiasm

The optic nerve is the first segment of the optic tract running from the eyeball to the optic chiasm (Fig. 2).

Each optic nerve is composed of around 0.8–1.2 millions of axons from ganglion cells, a number which decreases with age [11]. The axons originate from both the medial (nasal) portion and the lateral (temporal) portion of the retina to form each optic nerve [1], and are then fused together to form the optic chiasm [12, 13].

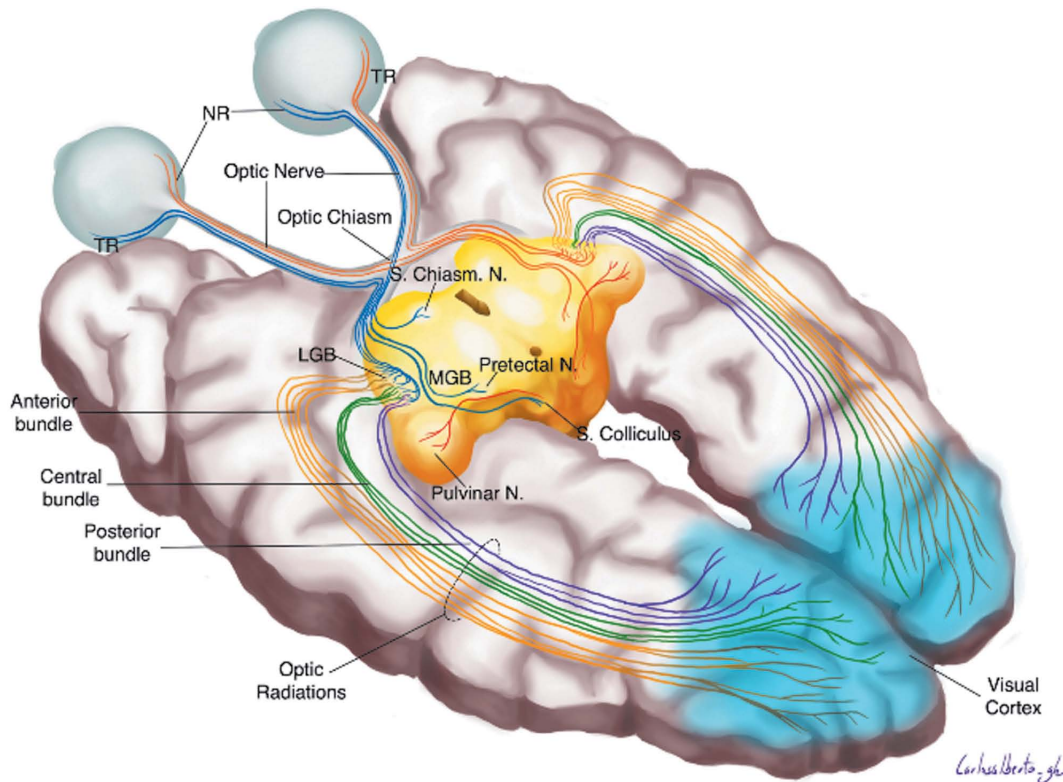


FIG. 2. Schematic illustration of the optical pathway.

Visual information received from nasal and temporal segments of both retinas (blue/orange lines) converges on each side in the optic fibres that form the optic nerve. In turn, both optic nerves fuse in the optic chiasm. Axons from the nasal portion of each retina decussate, while the temporal projections remain ipsilateral. Thus, each optical tract (blue/orange tracts) is made up of axons from the contralateral nasal retina and the ipsilateral temporal retina. In the LGB of the thalamus, geniculocalcarine radiations are divided into three bundles: anterior (Meyer's loop, yellow, upper half visual field), central (green, macula) and posterior (purple, lower visual field). From the optical tract, a set of axons of ganglion cells go towards the supra-chiasmatic nucleus to form the retinohypothalamic pathway. Light reflex is established by the emission of afferent projections towards the pretectal olivary nucleus. The saccade reflex is integrated through synaptic afferences towards the superior colliculi which in turn sends projections towards the pulvinar (red line).

РИС. 2. Схематическое изображение зрительного пути.

Зрительные импульсы, исходящие от носового и височного сегментов обеих сетчаток (синие/оранжевые линии), сходятся с каждой стороны в зрительных волокнах, которые образуют зрительный нерв. В свою очередь, оба зрительных нерва сливаются в зрительном перекресте. Аксоны от носовой части каждой сетчатки перекрещиваются, а волокна, идущие от височных половин каждой сетчатки, остаются ипсилатеральными. Таким образом, каждый зрительный путь (синий/оранжевый пучки) состоит из аксонов контралатеральной носовой сетчатки и ипсилатеральной височной сетчатки. В латеральном колленчатом теле таламуса колленчато-шпорный путь (зрительная лучистость) делится на три пучка волокон: передний (петля Мейера, желтый, верхняя половина поля зрения), центральный (зеленый, макула) и задний (фиолетовый, нижняя часть поля зрения). От зрительного пути множество аксонов ганглиозных клеток направляются к супрахиазматическому ядру, образуя ретиногипоталамический путь. Световой рефлекс возникает благодаря формированию афферентных проекций по направлению к оливарному претектальному ядру. Рефлекс саккады интегрируется через синаптическую передачу информации к верхнему холмику, который, в свою очередь, посылает проекции к пульвинарному ядру (красная линия).

Note: LGB – lateral geniculate body; MGB – medial geniculate body; NR – nasal retina; Pretectal N. – pretectal nucleus; Pulvinar N. – pulvinar nucleus; S. Colliculus – superior colliculus; S. Chiasm. N – supra chiasmatic nucleus; TR – temporal retina.

Примечание: LGB (lateral geniculate body) – латеральное колленчатое тело; MGB (medial geniculate body) – медиальное колленчатое тело; NR (nasal retina) – носовая сетчатка; Pretectal N. (pretectal nucleus) – претектальное ядро; Pulvinar N. (pulvinar nucleus) – пульвинарное ядро; S. Colliculus (superior colliculus) – верхний холмик; S. Chiasm. N (supra chiasmatic nucleus) – супрахиазматическое ядро; TR (temporal retina) – височная сетчатка.

The optic chiasm is the anatomical structure where fibres from both nasal parts of the retina intersect and are joined to the temporal tracts. The number of fibres which cross is greater than those which do not; this is vital for binocular vision as chiasmatic decussation combines information from the halves of each retina of the same visual field [13].

From the optic chiasm, the axons continue through the optic tract, but a specific type of retinal ganglion cell axon, which characteristically contain a photo-sensitive pigment called melanopsin, leave the chiasm and project toward the suprachiasmatic nucleus [14]. This establishes the retinohypothalamic pathway (Fig. 2) which contributes to controlling the circadian cycle [15].

Optic tract, lateral geniculate body, and optic radiations

Following chiasmatic decussation, the set of axons which comes from the ipsilateral temporal retina and the contralateral nasal retina compose each optic tract. Their primary target is the thalamus, where they establish a synaptic relay and then move on to the visual cortex or other central structures [6].

A small number of fibres are sent towards the dorsal midbrain and synapse with neurons in the superior colliculi, relevant for eye and head movements (saccade) in response to visual stimuli [16]. Another set of fibres project to the pretectal area to innervate the pretectal olivary nucleus (Fig. 2 and 3) that send axons to both Edinger-Westphal nuclei. Parasympathetic neuronal

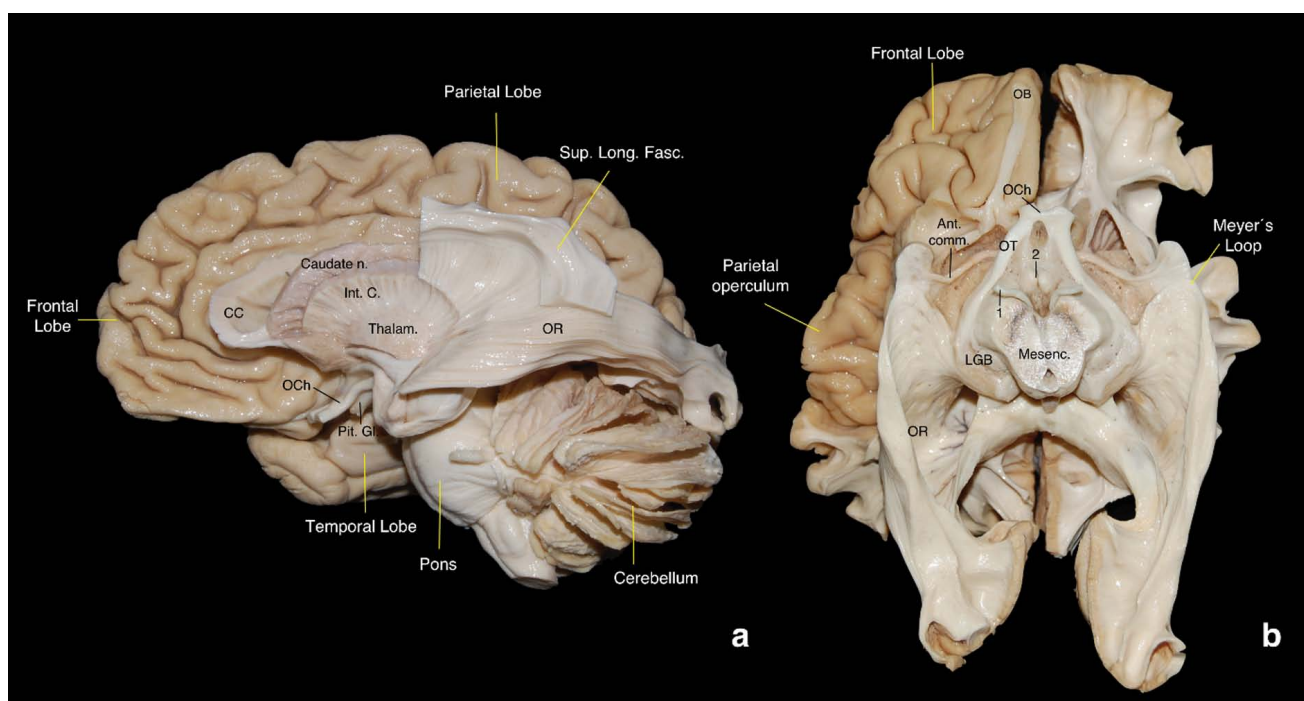


FIG. 3. Sagittal view (a) and basal surface (b) of a white matter fibres dissection of the optic radiations.

a. The fibres emerge from the thalamus lateral geniculate body laterally coursing in the roof of the temporal horn towards the primary visual cortex passing laterally to the atrium.

b. Optic radiation fibres from the lower part of the geniculate body loop forward and downward, forming the Meyer's loop, then turn back to join the central and posterior groups until they reach the calcarine fissure.

РИС. 3. Сагиттальный вид (а) и базальная поверхность (б) диссекции волокон белого вещества зрительной лучистости.

а. Волокна выходят из латерального коленчатого тела таламуса латерально, идут в крыше височного рога к первичной зрительной коре, проходя латерально к предсердию.

б. Волокна зрительной лучистости из нижней части коленчатого тела направляются вперед и вниз, образуя петлю Мейера, затем поворачивают назад, чтобы присоединиться к центральной и задней группам волокон, пока не достигнут калькариновой щели.

Note: 1 – oculomotor nerve (cranial nerve III); 2 – mammillary bodies; Ant. comm. – anterior commissure; Caudate n. – caudate nucleus; Int. C. – internal capsule; LGB – lateral geniculate body; Mesenc. – mesencephalon; OB – olfactory bulb; OCh – optic chiasma; OT – optic tract; Parietal L. – parietal lobe; Pit. GL. – pituitary gland; Sup. Long. Fasc. – superior longitudinal fasciculus; Thalam. – thalamus.

Примечание: 1 – глазодвигательный нерв (черепной нерв III); 2 – мамиллярные тела; Ant. comm. (anterior commissure) – передняя спайка; Caudate n. (caudate nucleus) – хвостатое ядро; Int. C. (internal capsule) – внутренняя капсула; LGB (lateral geniculate body) – латеральное коленчатое тело; Mesenc. (mesencephalon) – мезенцефалон; OB (olfactory bulb) – обонятельная луковица; OCh (optic chiasma) – зрительный перекрест; OT (optic tract) – зрительный путь; Parietal L. (parietal lobe) – теменная доля; Pit. GL. (pituitary gland) – гипофиз; Sup. Long. Fasc. (superior longitudinal fasciculus) – верхний продольный пучок; Thalam. (thalamus) – таламус.

relays are then directed to the ciliary ganglion and innervate the ciliary muscle, integrating the circuit for light reflex in both pupils [17].

The main target of the optic tract in the posterior thalamus is the lateral geniculate body, a six-layered structure localized lateral and caudal to the pulvinar, which comprises the first relay between retinal cells and the cerebral cortex [18]. The fourth-order neurons from each lateral geniculate body project ipsilaterally to the primary visual cortex (Brodmann area 17 or striate cortex) of the occipital lobe forming the geniculocalcarine tract [6, 19].

Based on microsurgical anatomical studies [19, 20] and in diffusion tensor imaging technology [6], the trajectory and anatomical relationships of optical radiations have been detailed. Three bundles have been described in this tract (Fig. 2 and 3): anterior, central and posterior [6]. The anterior bundle carries visual information from the lower retina (lower contralateral visual quadrant), runs

through the temporal lobe (Meyer’s loop) and terminates at the lingual gyrus. The posterior bundle represents the superior retina (upper contralateral visual quadrant), goes through the parietal lobe, and ends at the cuneus gyrus. The central bundle transmits macular information [6, 19, 20].

MICROSURGICAL ANATOMY OF THE OPTIC NERVE

According to Bernstein et al. (2016), the optic nerve is 43 to 47 mm long from globe to chiasm [21]. For its study, it is divided into four segments (Fig. 4a and 4b): intraocular, intraorbital, intra-canalicular, and intracranial [22].

Intraocular segment

Also known as the optic disc or optic nerve head, it is located inside the sclera and measures 0.91–2.91 mm

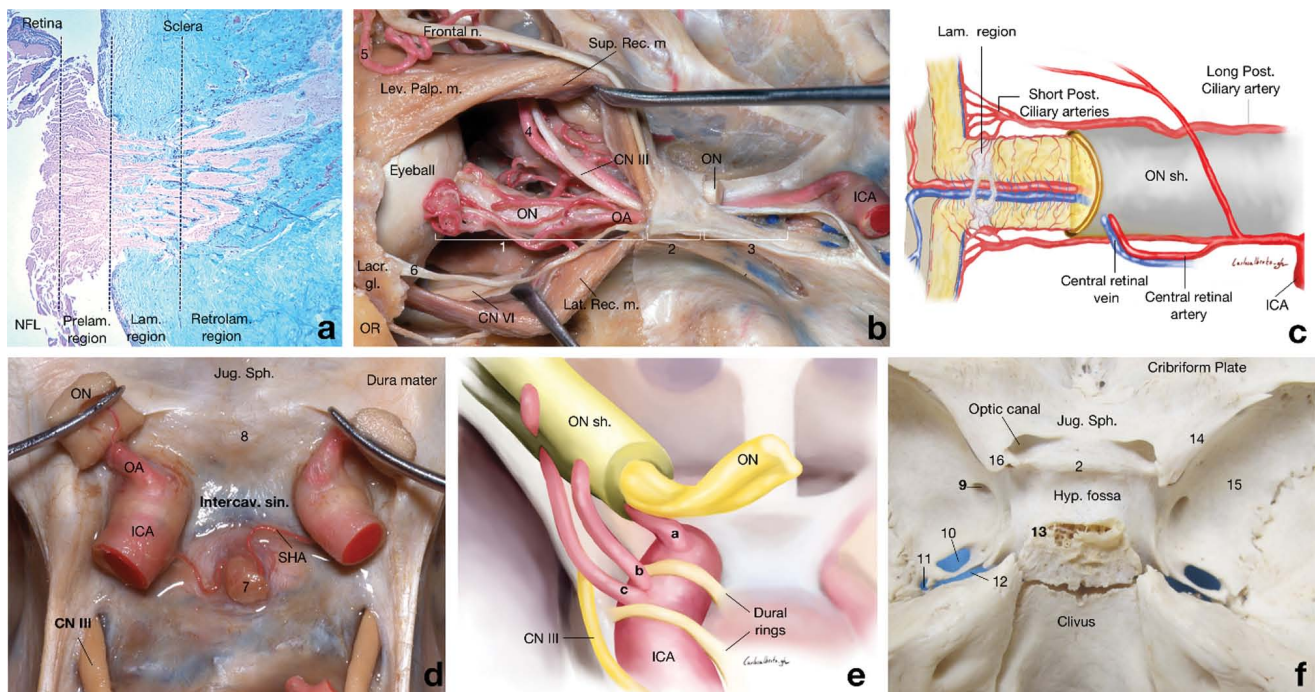


FIG. 4. Microsurgical anatomy intraocular, intraorbital, and intracanalicular segments of the optic nerve.
 a. Photomicrograph of a histological section of optic nerve stained with Masson’s trichrome stain, showing the optic disc and its four portions. It is possible to observe the pores that form between the connective tissue fibres through which the axons cross. A fragment of the retina and sclera is shown.
 b. Sagittal view of the optic nerve in cadaveric dissection. The lateral and superior rectus muscles have been retracted and the peri-orbital fat removed to expose the intra-orbital, intracanalicular, and the first portion of the intracranial segments. Anatomical relationships of the optic nerve with neighbouring structures such as blood vessels and muscle are shown. The anterior clinoid has been partially removed and the annular tendon opened so that the origin of the ophthalmic artery from the internal carotid artery and its intra-orbital pathway can be seen, but the intracanalicular segment remains hidden as its short longitude is covered with the annular tendon surrounding the orbital end of the optic foramen.
 c. Schematic illustration of the vascular supply of the optic nerve and structures of the eye.
 d. Unroofed optic canal to show the intra-canalicular segment of the optic nerve without the optic sheath to reflect it upwards and uncover the intradural type of the ophthalmic artery.
 e. Schematic illustration of the ophthalmic artery classification: intradural type (a), extradural supraoptic strut type (b) and extradural transoptic strut type (c).
 f. Upper view of the osseous relationships of the sphenoid bone and its foramina, including the optic canal.

РИС. 4. Микрохирургическая анатомия внутриглазного, интраорбитального и интраканального сегментов зрительного нерва.

- a. Фотомикрография гистологического среза зрительного нерва, окрашенного трихромным методом по Массону, на которой виден диск зрительного нерва и его четыре части. Можно наблюдать поры, образующиеся между волокнами соединительной ткани, через которые проходят аксоны. Показан фрагмент сетчатки и склеры.
- b. Сагиттальный вид зрительного нерва при препарировании трупа. Латеральная и верхняя прямая мышцы отведены ретрактором, периорбитальный жир удален, чтобы обнажить внутриорбитальный, внутриканальный и первую часть внутричерепного сегмента. Показаны анатомические взаимоотношения зрительного нерва с соседними структурами, такими как кровеносные сосуды и мышцы. Передний наклоненный отросток частично удален, кольцевидное сухожилие вскрыто таким образом, что видно начало глазной артерии от внутренней сонной артерии и ее интраорбитальная часть, но внутриканальный сегмент остается скрытым, так как его короткая продольная линия закрыта кольцевидным сухожилием, окружающим орбитальный конец зрительного канала.
- c. Схематическая иллюстрация системы кровоснабжения зрительного нерва и структур глаза.
- d. Крыша зрительного канала удалена, чтобы показать сегмент зрительного нерва внутри канала без оболочки зрительного нерва для отображения его направления вверх и демонстрации интрадурального типа локализации глазной артерии.
- e. Схематическая иллюстрация классификации локализаций глазной артерии: интрадуральный тип (a), экстрадуральный тип (проходит над зрительной перегородкой (задней ножкой малого крыла клиновидной кости)) (b) и экстрадуральный тип (проходит через зрительную перегородку (заднюю ножку малого крыла клиновидной кости)) (c).
- f. Вид сверху на костные взаимоотношения клиновидной кости и ее отверстий, включая зрительный канал.

Note: CN III – cranial nerve III (oculomotor nerve); CN VI – cranial nerve VI (abducens nerve); Frontal L. – frontal lobe; Frontal n. – frontal nerve; Hyp. Fossa – hypophysial fossa; ICA – internal carotid artery; Intercav. Sin. – intercavernous sinus; Jug. Sph. – jugum sphenoidale; Lam region – lamina cribrosa region; Lat. Rec. m. – lateral rectus muscle; Lev. Palp. m. – levator palpebrae muscle; Long Post. Ciliary artery – long posterior ciliary artery; OA – ophthalmic artery; ON – Optic nerve; ON sh. – optic nerve sheath; OR – orbital rim; Prelam. Region – prelaminar region; Retrolam. Region – retrolaminar region; SHA – superior hypophysial artery; Short Post. Ciliary arteries – short posterior ciliary arteries; Sup. Rec. m. – superior rectus muscle; Temporal L. – temporal lobe; 1 – intraorbital segment of the optic nerve; 2 – intracanalicular segment of the optic nerve; 3 – intracranial segment of the optic nerve; 4 – anterior ethmoidal artery; 5 – supratrochlear artery; 6 – lacrimal nerve; 7 – infundibulum; 8 – tuberculum sellae; 9 – foramen rotundum; 10 – foramen ovale; 11 – foramen spinosum; 12 – foramen lacerum; 13 – posterior clinoid process; 14 – lesser wing of sphenoid bone; 15 – greater wing of sphenoid bone; 16 – anterior clinoid process.

Примечание: CN III (cranial nerve III) – черепной нерв III (глазодвигательный нерв); CN VI (cranial nerve VI) – черепной нерв VI (возвратный нерв); Frontal L. (frontal lobe) – лобная доля; Frontal n. (frontal nerve) – лобный нерв; Hyp. Fossa (hypophysial fossa) – гипофизарная ямка; ICA (internal carotid artery) – внутренняя сонная артерия; Intercav. Sin. (intercavernous sinus) – интеркавернозный синус; Jug. Sph. (jugum sphenoidale) – клиновидное возвышение; Lam region (lamina cribrosa region) – область решетчатой пластинки; Lat. Rec. m. (lateral rectus muscle) – латеральная прямая мышца; Lev. Palp. m. (levator palpebrae muscle) – леватор пальпебральной мышцы; Long Post. Ciliary artery (long posterior ciliary artery) – длинная задняя цилиарная артерия; OA (ophthalmic artery) – глазная артерия; ON – (optic nerve) зрительный нерв; ON sh. (optic nerve sheath) – оболочка зрительного нерва; OR (orbital rim) – орбитальный ободок; Prelam. Region (prelaminar region) – преламинарная область; Retrolam. Region (retrolaminar region) – ретроламинарная область; SHA (superior hypophysial artery) – верхняя гипофизарная артерия; Short Post. Ciliary arteries (short posterior ciliary arteries) – короткие задние цилиарные артерии; Sup. Rec. m. (superior rectus muscle) – верхняя прямая мышца; Temporal L. (temporal lobe) – височная доля; 1 – внутриорбитальный сегмент зрительного нерва; 2 – внутриканальцевый сегмент зрительного нерва; 3 – внутричерепной сегмент зрительного нерва; 4 – передняя этмоидальная артерия; 5 – супратрохлеарная артерия; 6 – слезный нерв; 7 – инфундибулум; 8 – бугорок турецкого седла; 9 – круглое отверстие; 10 – овальное отверстие; 11 – остистое отверстие; 12 – равное отверстие; 13 – задний наклоненный отросток; 14 – малое крыло клиновидной кости; 15 – большое крыло клиновидной кости; 16 – передний наклоненный отросток.

long at its largest diameter, with the horizontal diameter usually smaller than the vertical [23]. The choriocleral canal, shaped like a cone and found at the level of Bruch's membrane, determines the shape and dimension of the vertical diameter, which generally measures 1.5–1.9 mm [1, 23]. Four regions, front to back, can be identified in this portion (Fig. 4a): 1) superficial nerve fibre layer; 2) prelaminar region; 3) lamina cribrosa region; and 4) retrolaminar region [24].

The most anterior region is the superficial nerve fibre layer, composed mainly of ganglion cell axons, and separated from the vitreous by the (Elsching's) inner limiting membrane, which in turn is continuous with the inner limiting barrier of the retina. The prelaminar region behind the latter is composed of astrocytes and a superficial capillary network as well as tributaries of the retinal vessels immersed in supporting connective tissue, maintaining the viability of this first segment of the nerve [24, 25]. The prelaminar region is where pathological

changes such as optic disc oedema, glaucoma or anterior ischemic optic neuropathy can be detected [1].

The lamina cribrosa region, known as the scleral segment, has fibres similar to those in the prelaminar region, surrounded by concentric connective tissue fibres (elastin and collagen) forming pores through which the nerve fibres pass [26]. In the retrolaminar region, axons follow a parallel course to each other and are surrounded by astrocytic processes [24, 25]. The presence of oligodendrocytes documented in this layer coincides with the onset of the myelinated portion of the nerve, 400 to 500 um beyond the laminar region limit [27]. Intraretinal myelination of ganglion cell axons is present in 1% of the human population [28].

The retinal vascular supply comes from the retinal artery. The retinal and choroid circulation supply the prelaminar region; the laminar region is supplied by the posterior ciliary short arteries (branches of the ophthalmic artery) and the retrolaminar region by the

pial arteries (Fig. 4c). Its venous drainage is provided by the central vein of the retina [29].

Intraorbital segment

This segment constitutes the area from the eyeball to the optical canal, with an approximate length of 25–30 mm and a larger diameter than the intraocular (3 to 4 mm) because of the myelin [1]. From the retrolaminar region, once it emerges from the eyeball, it is coated by the typical meningeal layers: the pia mater and arachnoid membranes continuations of the choroid; and by the dura mater from the connective tissue of the sclera (Fig. 4b). A subarachnoid space is therefore generated which continues to the intracranial segment and central structures. This anatomical condition explains optic disc oedema as a consequence of intracranial hypertension [30].

This segment is in relation with the muscles of the orbit initially separated by fat but as it approaches the entry point into the optic canal, its sheath binds to the tendon fibres of the upper oblique, medial straight and upper rectus muscles. The ciliary ganglion is found between the rectus lateralis muscle and the lateral wall of the optic nerve [31]. In this portion, the optic nerve is medial to the annular tendon and below the elevator muscles of the eyelid and superior rectus muscles (Fig. 4b). The surrounding dura mater of the optic nerve is attached to the annular tendon [31].

In this segment, irrigation is dependent on the ophthalmic artery (Fig. 4c and 4d). Anatomical studies report that in 75% of specimens its origin is in the anteromedial or superomedial faces of the supraclinoid segment of the internal carotid artery (Fig. 4d and 4e) [30, 32, 33]. Other reported origins are in the intradural segment [34], the middle meningeal artery [35] and even the anterior cerebral artery [35]. The optic canal is the entrance site of the ophthalmic artery to the cranial cavity (Fig. 4f), usually inferolateral in relation to the optic nerve [36, 37]. On its intraorbital trajectory, the artery travels immersed in the dural covering of the optic nerve usually on its inferolateral edge for the first third of the path to the eyeball (Fig. 4d). It is then angulated to cross either over (in 83% of cases) or under (17%) the optic nerve, adjacent to the superior rectus muscle (Fig. 4e), as observed by S.S. Hayreh in 61 specimens [36]. The final segment runs medial to the optic nerve to finish at the superomedial angle of the orbit (Fig. 4b) [38].

The ophthalmic artery branches to the central retinal artery or, less commonly, can arise from the posterior ciliary or a muscular branch [39]. This artery penetrates the dural sheath and the nerve inferomedially (mainly) or inferolaterally, approximately 11 mm from the sclera, to run centrally through the nerve, along with the central vein until reaching the retina [39]. The ophthalmic artery also gives rise to short and long ciliary arteries that emit multiple small branches that penetrate the nerve and form the pial plexus, which in turn anastomosed by branches of the central artery of the retina to irrigate

the intraorbital segment of the optic nerve (Fig. 4b and 4c). The ciliary arteries also irrigate the structures of the eyeball [40].

Intracanalicular segment

This corresponds to the segment that runs through the optic canal (Fig. 4b), with an approximate length of 5 to 10 mm, and is attached to the Zinn's ring making it the segment that is most susceptible to compression [41]. On its canalicular pathway, the nerve is covered medially by a small layer of bone in relation to the sphenoidal recess and ethmoid cells, and between these are sphenothmoid or Onodi cells [41, 42]. According to K. Fujii et al., 4% of the population does not have this layer of bone, so the nerve is in direct contact with the sphenoidal sinus and 8% of the population has no bone covering of the carotid artery in the sphenoidal sinus [43]. Due to its trajectory, an impression is made on the sphenoidal sinus and, depending on the protuberance, it can be divided into four types: type 1 nerves course adjacent to the sphenoid sinus with no indentation of the wall; type 2 nerves course adjacent to the sphenoidal sinus, causing indentation of the sinus wall; type 3 nerves course through the sphenoid sinus; type 4 nerves course immediately adjacent to the sphenoidal sinus and the posterior ethmoidal air cell. These variants are also called non-impression, impression, semi-canal and canal, respectively [44].

The optic canal is composed of four walls (Fig. 4f): 1) The optical abutment or the posterior root of the sphenoid (inferior wall); 2) the body of the sphenoid (medial wall); 3) the anterior or superior root of the lesser sphenoid wing (superior wall); and 4) the anterior clinoid process (lateral wall) [42]. If a straight line is drawn from the frontozygomatic suture in the medial direction, the optical canal is at approximately 13 mm [37].

With a width of 4 to 5mm and a length of approximately 10mm, the canal becomes thinner as it approaches the eyeball, although the subarachnoid space surrounding the intracranial segment of the optic nerve is continuous with the intracranial portion [37]. Once in the optical canal, the dura mater fuses to form the periorbital connective tissue [37, 41, 45]. It is in the optical canal where the optic nerve is closely related to the ophthalmic artery, from which it receives its major irrigation, found in an inferolateral situation going to inferomedial in the next segment [37].

Intracranial segment

This segment is only 10mm long [46]; the nerve rests on the sellar diaphragm, and more dorsally is in relation to the cavernous sinus, covered only by the pia mater in all its trajectory at this level up to the entry of the optic canal [1, 40]. The irrigation of this segment is provided by branches of the anterior cerebral artery, internal carotid artery, and anterior communicating artery (Fig. 5a and 5b) [40].

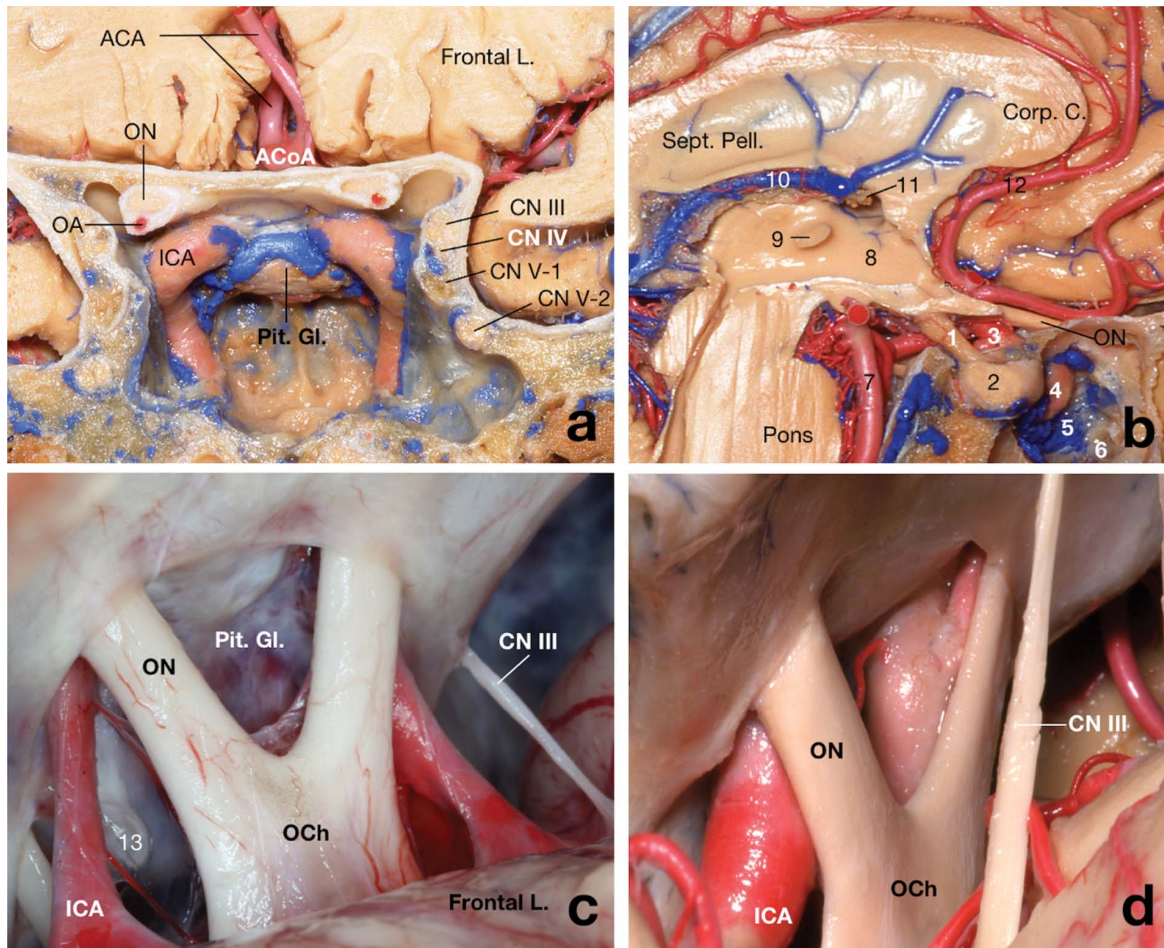


FIG. 5. Intracranial trajectory of the optic nerve.

- a. Coronal section with a view of the pituitary gland and the optic nerves and chiasm below. The ophthalmic artery runs immersed in the dural covering of the optic nerve on its inferior edge.
 b. Sagittal view of the sellar region, suprasellar area and third ventricle. Above the sella the infundibulum and optic chiasma, and between the later and the lamina terminalis we find the suprachiasmatic recess of the third ventricle.
 c. Postfixed variation of the optic chiasma on a subfrontal approach.
 d. Normal variation of the optic chiasma on a pterional approach.

РИС. 5. Внутричерепная траектория зрительного нерва.

- a. Корональный срез с видом на гипофиз и расположенные ниже зрительные нервы и хиазму. Глазная артерия проходит в дуральной оболочке зрительного нерва по его нижнему краю.
 b. Сагиттальный вид седлярной области, надседлярной области и третьего желудочка. Над турецким седлом находятся воронка гипофиза и зрительный перекрест, а между ними и терминальная пластинка – супрахиазматическое углубление третьего желудочка.
 c. Постфиксированная вариация зрительного перекреста при субфронтальном доступе.
 d. Нормальная вариация зрительного перекреста при птериональном доступе.

Note: ACA – anterior cerebral artery; ACoA – anterior communicating artery; CN III – cranial nerve III (oculomotor nerve); CN IV – cranial nerve IV (trochlear nerve); CN V-1 – ophthalmic division of trigeminal nerve; CN V-2 – maxillary division of trigeminal nerve; Corp. C. – corpus callosum; Frontal L. – frontal lobe; ICA – internal carotid artery; Och – optic chiasma; ON – optic nerve; Pit. Gl. – pituitary gland; Sept. Pell. – septum pellucidum; 1 – infundibulum; 2 – tuberculum sellae; 3 – ICA supraclinoid segment; 4 – ICA intracavernous segment; 5 – cavernous sinus; 6 – sphenoidal sinus; 7 – basilar artery; 8 – third ventricle; 9 – interthalamic adhesion; 10 – anterior vein of septum pellucidum; 11 – choroid plexus; 12 – pericallosal artery; 13 – posterior clinoid process.

Примечание: ACA (anterior cerebral artery) – передняя мозговая артерия; ACoA (anterior communicating artery) – передняя соединяющая артерия; CN III (cranial nerve III) – черепной нерв III (глазодвигательный нерв); CN IV (cranial nerve IV) – черепной нерв IV (трохлеарный нерв); CN V-1 – офтальмологический отдел тройничного нерва; CN V-2 – верхнечелюстной отдел тройничного нерва; Corp. C. (corpus callosum) – мозолистое тело; Frontal L. (frontal lobe) – лобная доля; ICA (internal carotid artery) – внутренняя сонная артерия (BCA); Och (optic chiasma) – зрительный перекрест; ON (optic nerve) – зрительный нерв; Pit. Gl. (pituitary gland) – гипофиз; Sept. Pell. (septum pellucidum) – прозрачная перегородка; 1 – воронка гипофиза; 2 – бугорок турецкого седла; 3 – супраклиноидный сегмент BCA; 4 – интракавернозный сегмент BCA; 5 – кавернозная пазуха; 6 – клиновидная пазуха; 7 – базилярная артерия; 8 – третий желудочек; 9 – межталамическая спайка; 10 – передняя вена прозрачной перегородки; 11 – сосудистое сплетение; 12 – околomosозлистая артерия; 13 – задний наклоненный отросток.

At the opening of the optic canal, there is a fold of dura mater known as the falciform process which lies over it, covering it by several millimetres medially following the anterior clinoid processes [37, 45]. As each nerve emerges from the optic canal they adopt an angle of 45 degrees and, after a short path, fuse to the contralateral nerve to form the optic chiasm, taking a medial position to the internal carotid and lower frontal lobe (Fig. 5a and 5b) [12].

Optic chiasm

The optic chiasm, covered with arachnoid and pia mater has an anteroposterior diameter of 4 to 13mm, a

width of 3 to 5 mm, and a transverse diameter of 4 to 13 mm [12]. The incisura of tentorium is crossed by the anterior part of the optic tract, chiasm and optic nerves [12, 47].

The chiasm (Fig. 5c and 5d) is located in the suprasellar cistern, below the hypothalamus, 10mm above the pituitary gland and sellar diaphragm, in front of the pituitary stem [12]. In front of the chiasm, we find the continuation of the subarachnoid space, through which the intracranial portion continues, with third ventricle behind and above [48]. The anterior cerebral artery and the anterior communicating artery run above the optic chiasm [40].

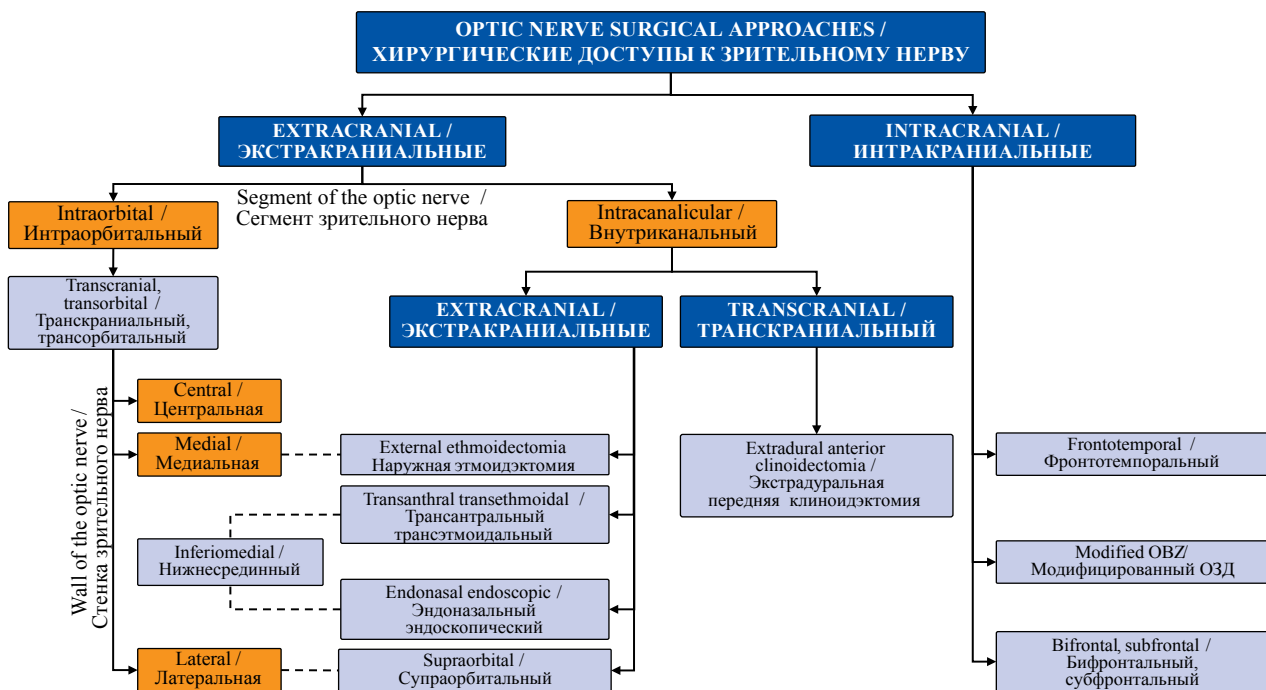


FIG. 6. Surgical approach algorithm for each of the optic tracts.

Extracranial approaches are chosen for the intraorbital segment, susceptible to optic nerve gliomas, to reach the central, medial, and lateral walls of the nerve. Here, the transcranial-transorbital medial approach is the first choice but some endoscopic approach could also reach the medial and lateral walls (dashed lines). For the Intracanalicular segment, mainly injured by trauma, minimally invasive endoscopic endonasal approaches could be undertaken (external ethmoidectomy, transantral transethmoidal or endonasal endoscopic) reaching the medial/lateral/inferomedial walls of the segment, but when required a combination of transcranial/supraorbital approach with an extradural anterior clinoidectomy gives better decompression as it allows the opening of the annular tendon. If the lesion affects the intracranial segment, most commonly in tumours, an intracranial approach should be undertaken: frontotemporal, modified orbitozygomatic (OBZ) and bifrontal/subfrontal or the minimally invasive supraorbital approach.

РИС. 6. Алгоритм хирургического доступа для каждого из зрительных трактов.

Для внутриорбитального сегмента, подверженного глиомам зрительного нерва, выбираются экстракраниальные доступы, чтобы достичь центральной, медиальной и латеральной стенок нерва. Здесь транскраниально-трансорбитальный медиальный доступ является первым выбором, но через некоторые эндоскопические доступы также можно достичь медиальной и латеральной стенок (пунктирные линии). Для внутриканального сегмента, в основном поврежденного в результате травмы, могут быть применены малоинвазивные эндоскопические эндоназальные доступы (наружная этмоидэктомия, трансантральный трансэтмоидальный или эндоназальный эндоскопический), достигающие медиальной/латеральной/инферомедиальной стенок сегмента, но при необходимости сочетание транскраниального/супраорбитального доступа с экстрадуральной передней клиноидэктомией дает лучшую декомпрессию, так как позволяет открыть кольцевидное сухожилие. Если поражение затрагивает внутричерепной сегмент, чаще всего при опухолях, следует применить интракраниальный доступ: фронтотемпоральный, модифицированный орбитозигматический (OBZ – orbitozygomatic) и бифронтальный/субфронтальный или минимально инвазивный супраорбитальный доступ.

Note: OBZ – orbitozygomatic.

Примечание: ОЗД – орбитозигматический доступ.

Although uncommon, there are anatomical variants where the intracranial portion of the optic nerve may be so long or so short that the chiasm is not found in relation to the sellar diaphragm or the pituitary gland [49]. The two variants are: prefixed (Fig. 5d) which lays more anteriorly in relation to the tuberculum sellae, and postfixed (Fig. 5c) found over the dorsum sellae [12, 48]. The importance of identifying them is that a prefixed chiasm or a protruding tuberculum will limit access to the sellar and suprasellar region in a transcranial approach [31, 47].

NEUROSURGICAL APPROACHES TO THE OPTIC NERVE

Depending on the segment to be approached, we suggest an algorithm to choose the most suitable and effective surgical approach for the optic nerve (Fig. 6). For the intraorbital segment, the orbital bones are taken as reference, dividing the nerve in a lower, upper, lateral, and medial face. The lesions that most commonly affect this area and are surgically treatable are neoplasms derived from glia and the optic nerve sheath [31]. The intracanalicular segment is, as explained before, the site of surgical decompression, with either an extracranial or transcranial approach [50]. There are several open extracranial approaches as well as minimally invasive

AUTHOR CONTRIBUTIONS

R. López-Elizalde: project development, cadaveric dissection and photography, manuscript writing. M. Godínez-Rubi: project development, manuscript writing, photography. Y. Lemus-Rodríguez: project development, literature search, manuscript writing. E. Mercado-Rojas: literature search, manuscript writing. T. Sánchez-Delgadillo: literature search, manuscript writing. D. Sánchez-Delgadillo: literature search, manuscript writing. Á. Campero: cadaveric dissection, critical review of the manuscript. R.G. Párraga: cadaveric dissection. All authors participated in the discussion and editing of the work. All authors approved the final version of the publication.

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endoscopic ones, but these only release the Zinn's ring and not the falciform ligament. This only being possible via a transcranial approach as required in trauma or tumours [42]. Finally, in the intracranial segment affected by tumoral lesions such as sellar or clinoid tubercular meningiomas, a working angle for removal of the lesion allowing decompression of the respective nerves or infiltrated ones is required [51].

CONCLUSION

When a surgery which involves the optic nerve is planned, the surgeon must have knowledge of both the functional and microsurgical anatomy to preserve the important neurovascular structures surrounding the nerve. While it is true that most postoperative complications are resolved without sequelae, others involving the vascular structures can result in significant visual loss, forever changing the lifestyle of the patient. Therefore, surgical approaches to the optic nerve use intracranial and extracranial nerve location as criteria to consider the structures we must manipulate in each segment. Understanding and using this knowledge provides the foundation to choose and perform successful neurosurgical approaches without increasing such morbidity.

ВКЛАД АВТОРОВ

Р. Лопес-Элизальде: разработка проекта, препарирование и фотография трупов, написание рукописи. М. Годи́нес-Руби: разработка проекта, написание рукописи, фотография. Я. Лемус-Родри́гес: разработка проекта, поиск литературы, написание рукописи. Э. Меркадо-Рохас: поиск литературы, написание рукописи. Т. Санчес-Дельгадильо: поиск литературы, написание рукописи. Д. Санчес-Дельгадильо: поиск литературы, написание рукописи. А. Камперо: препарирование трупов, критический обзор рукописи. Р.Г. Паррага: препарирование трупов. Все авторы принимали участие в обсуждении и редактировании работы. Все авторы одобрили окончательный вариант публикации.

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INFORMATION ABOUT THE AUTHORS / ИНФОРМАЦИЯ ОБ АВТОРАХ

Ramiro López-Elizalde[✉], MD, Health Regulatory Directorate, Instituto de Seguridad y Servicios Sociales de los Trabajadores del Estado, Ciudad de México, México.

ORCID: <https://orcid.org/0000-0002-7515-7710>

Marisol Godínez-Rubí, MD, PhD, Laboratorio de Investigación en Patología, Departamento de Microbiología y Patología, Centro Universitario de Ciencias de la Salud, Universidad de Guadalajara, Guadalajara, Jalisco, Mexico.

ORCID: <https://orcid.org/0000-0002-6779-1017>

Yazmín Lemus-Rodríguez, MD, Servicio de Neurocirugía, Hospital General Dr. Valentín Gómez Farías, ISSSTE, Guadalajara, Jalisco, Mexico.

ORCID: <https://orcid.org/0000-0001-5354-1749>

Elizabeth Mercado-Rojas, MD, Servicio de Neurocirugía, OPD Hospital Civil Juan I. Menchaca, Guadalajara, Jalisco, Mexico.

ORCID: <https://orcid.org/0000-0001-6541-8609>

Tania Sánchez-Delgadillo, MD, Servicio de Neurocirugía, Hospital General Dr. Valentín Gómez Farías, ISSSTE, Guadalajara, Jalisco, Mexico.

ORCID: <https://orcid.org/0000-0001-5700-8589>

David Sánchez-Delgadillo, MD, Servicio de Neurocirugía, Hospital General Dr. Valentín Gómez Farías, ISSSTE, Guadalajara, Jalisco, Mexico.

ORCID: <https://orcid.org/0000-0003-0705-977X>

Álvaro Campero, MD, Servicio de Neurocirugía, Hospital Padilla, Tucumán, Argentina.

ORCID: <https://orcid.org/0000-0001-5184-5052>

Richard Gonzalo Párraga, MD, Instituto de Neurocirugía de Bolivia (INEB), Cochabamba, Bolivia.

ORCID: <https://orcid.org/0000-0001-9954-5219>

Рамиро Лопес-Элизальде[✉], MD, Медицинское управление, Институт социального обеспечения и услуг для государственных служащих, г. Мехико, Мексика.

ORCID: <https://orcid.org/0000-0002-7515-7710>

Марисоль Годи́нес-Руби, MD, PhD, Научно-исследовательская лаборатория патологии, кафедра микробиологии и патологии, Университетский центр наук о здоровье, Университет Гвадалахары, Гвадалахара, Халиско, Мексика.

ORCID: <https://orcid.org/0000-0002-6779-1017>

Язмин Лемус-Родригес, MD, Нейрохирургическая служба, Главный госпиталь доктора Валентина Гомеса Фариа-са, ISSSTE, Гвадалахара, Халиско, Мексика.

ORCID: <https://orcid.org/0000-0001-5354-1749>

Элизабет Меркадо-Рохас, MD, Нейрохирургическая служба, гражданская больница OPD Хуана И. Менчака, Гвадалахара, Халиско, Мексика.

ORCID: <https://orcid.org/0000-0001-6541-8609>

Таня Санчес-Дельгадильо, MD, Нейрохирургическая служба, Главный госпиталь доктора Валентина Гомеса Фариа-са, ISSSTE, Гвадалахара, Халиско, Мексика.

ORCID: <https://orcid.org/0000-0001-5700-8589>

Давид Санчес-Дельгадильо, MD, Нейрохирургическая служба, Главный госпиталь доктора Валентина Гомеса Фариа-са, ISSSTE, Гвадалахара, Халиско, Мексика.

ORCID: <https://orcid.org/0000-0003-0705-977X>

Альваро Камперо, MD, Отделение нейрохирургии, госпиталь Падилья, Тукуман, Аргентина.

ORCID: <https://orcid.org/0000-0001-5184-5052>

Ричард Гонсало Паррага, MD, Институт нейрохирургии Боливии (INEB), Кочабамба, Боливия.

ORCID: <https://orcid.org/0000-0001-9954-5219>

✉ Corresponding author / Автор, ответственный за переписку