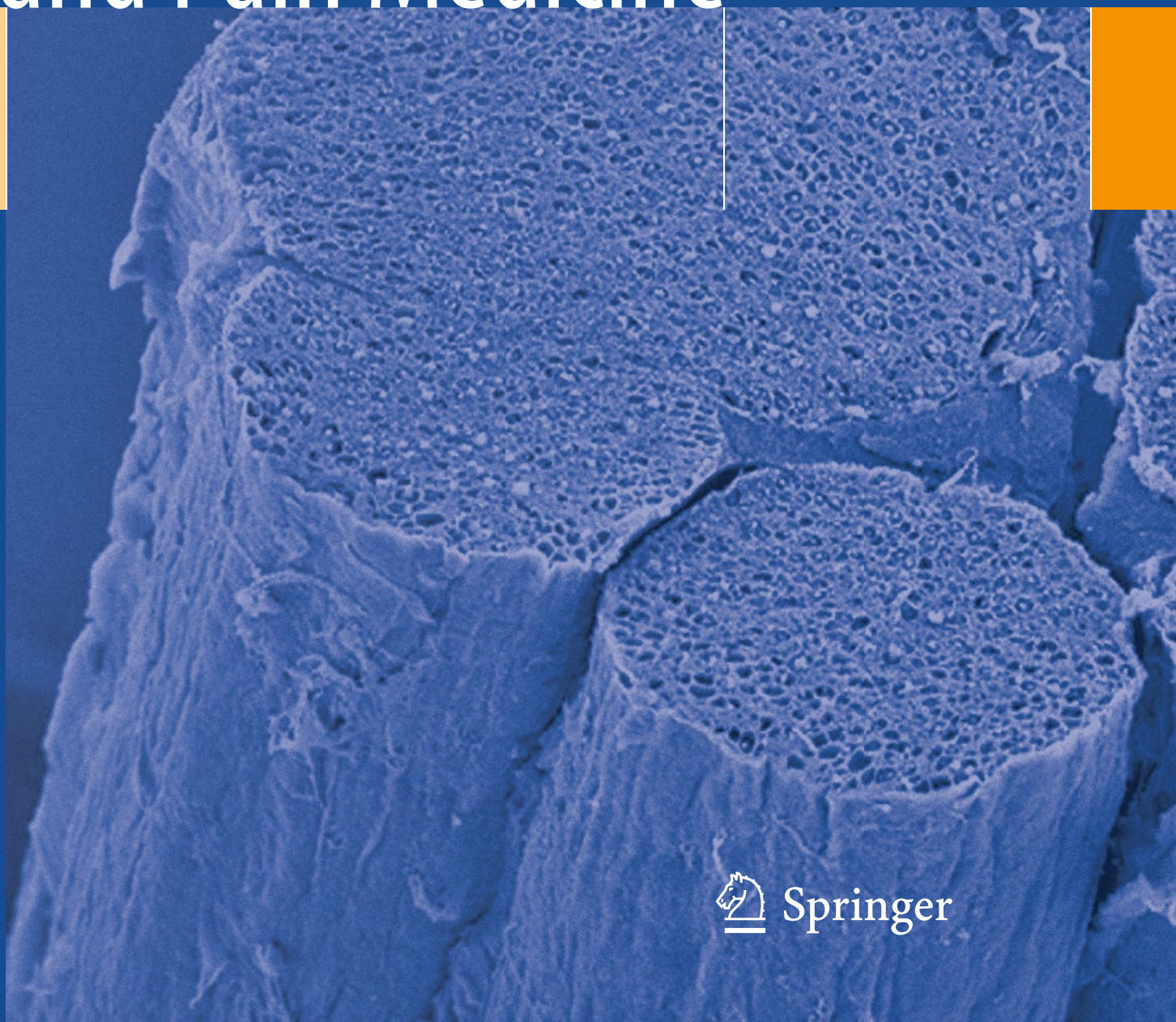
Miguel Angel Reina *Editor*
José Antonio De Andrés · Admir Hadzic · Alberto Prats-Galino
Xavier Sala-Blanch · André A.J. van Zundert *Associate Editors*

# Atlas of Functional Anatomy for Regional Anesthesia and Pain Medicine



Springer

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# Atlas of Functional Anatomy for Regional Anesthesia and Pain Medicine

## Human Structure, Ultrastructure and 3D Reconstruction Images

Springer

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*To my children, Yamila, Lucila, and Emmanuel, for their shared interest and for being the source of inspiration in the development of a lifelong project.*

*To my beloved wife, Emilse, for her enduring love and unconditional support and for transforming each day into a unique experience with the gift of her smile.*

# Preface

Several excellent books on anatomy and histology comprehensively address features of the entire human body. Some are based on drawings and sketches; others are collections of photographic images obtained from cadavers. In recent decades, not only anesthesiologists with an interest in techniques related to anesthetic blockades and pain treatment, but also orthopedic surgeons and neurosurgeons interested in surgical techniques on the spinal column have searched for answers to their inquiries through the pages of these types of books. The elaboration of atlases on general histology has enabled professionals to assess the role that human tissues play in processes related to the pharmacokinetics and pharmacodynamics of certain drugs such as the analysis of the possible mechanisms leading to several complications.

This Atlas is the result of anatomical and histological research oriented and applied to solve specific questions expressed by practitioners that may arise during clinical practice, with answers not often found in traditional general atlases.

Practitioners who carry out their activities in the operating room during long shifts may have difficulty finding time to research subjects of interest. Often, hypotheses supporting clinical investigations have been based on anatomy and general histology books.

Our inquiring minds prompted us to seek possible answers to problems befalling patients due to regional anesthetic practice in the operating room, leading us to revise in the laboratory basic concepts in anatomy and histology. In several instances, the search for answers with regard to needs in regional anesthesia and related medical specialties has enabled us to support previously published results, but in few occasions the opposite findings obtained in our studies led us to question theoretical considerations from books that had been traditionally accepted over the past century. Such is the case in our revision of the spinal dural sac in humans, where examination of its ultrastructure displayed differences that can no longer support the existence of a real subdural space as it had been described decades ago. Instead, the subdural space is an acquired space, in many cases of artifactual origin, due to manipulation during the process of sample extraction from cadavers. Evidence outlined here, as well as other facts discussed in this Atlas, raises awareness of the need for further critical review of many hypotheses to objectively analyze previous contradictory data.

The authors of chapters in this Atlas are experts in their respective fields of research who present images from their own work, offering relevant anatomical insights of interest to several medical disciplines. In an effort to improve scientific communication between researchers and readers, a great effort has been made to collect numerous recently acquired images in each chapter, with many remaining unpublished at present.

Instead of barely presenting facts in the form of a traditional textbook in which explanations are provided mainly in written form, this Atlas offers a brief introduction in each chapter but prioritizes the illustrating potential of real human images from tissue samples carefully selected to provide results open to inquiry and interpretation by the reader. Specialists may use this work as a source of information according to their own interests.

For this reason, we believe this Atlas closes a gap that existed in the past decade concerning new scientific research technologies of interest to anesthesiologists, orthopedic surgeons, neurosurgeons, and medical practitioners.

However, this Atlas is not intended to replace textbooks on regional anesthesia, techniques in the treatment of pain, or surgical techniques of the spine or peripheral nerves. Each chapter intends to act as complement and facilitate the understanding of chapters of books that do not have this type of graphic material.

The Atlas includes more than 1,600 images. Each image is followed by a short text to aid in its interpretation. The amount of work involved in obtaining these images extends over a period of 25 years.

The different types of images include those on gross anatomy obtained from anatomical dissections, specifically designed to meet the requirements of this Atlas. In addition, transmission and scanning electron microscopy images help to interpret the ultrastructure of tissues that may be of particular interest to professionals for whom this work is intended. Three-dimensional (3D) image reconstruction of magnetic resonance images (MRI) has become increasingly relevant as it can display 3D images of anatomical structures from different perspectives as well as their relationships, significantly meeting not only the diagnostic purposes of radiology departments but also the goals of several medical disciplines such as therapy units and educational departments' surgical units, among others.

The first part of the Atlas presents the macroscopic morphology of peripheral nerves along with their ultrastructure and the types of tissue damage that may be caused due to accidental puncture of these nerves. This part incorporates the analysis of anatomical models on which "in vitro" intraneural injections had been performed.

The second part presents the macroscopic morphology, ultrastructure, and 3D reconstructions obtained from MRIs of human spinal meninges, the nerve roots of the cauda equina, spinal ligaments, and epidural fat. This part includes chapters in which the ultrastructure of tissue damaged during "in vitro" lumbar punctures is examined, adopting anatomical models to illustrate injuries caused by different types of needle tips of routine use during regional anesthesia. Similar models are presented to evaluate the consequences of selective root anesthetic blocks and to assess spinal devices for neurostimulation instruction.

The third part of the Atlas describes devices required in the realization of anesthetic blocks, each displayed and examined in an illustrative manner, including different types of needles and catheters used in central and peripheral blockade and relevant features of epidural filters.

Finally in the fourth part, chapters are organized by methodological aspects relative to techniques applied in the production of images illustrating this Atlas.

The authors have made a significant effort to produce a remarkable collection of scientific images. Their work also reveals its message in part through brief elucidating descriptions that accompany these images. Each of these images contains details that may support or challenge current concepts accepted in our clinical practice. Facts are exposed in this Atlas to serve the purpose of presenting current insights and controversies to readers. It is our hope that reviews of scientific work may help strengthen the foundations of medical knowledge to benefit clinical practice, which has no other aim than caring for patients worldwide.

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I would like to thank Dr. Andrés López, who has actively collaborated and supported this research for more than 20 years as Head of Department of Anesthesiology HM University Hospitals. I wish to extend my gratitude to all physicians and technical staff at the Madrid-Montepríncipe University Hospital, and the Faculty of Medicine of the Universidad CEU San Pablo, in particular to the technical staff at the Institute of Applied Molecular Medicine.

I would also like to thank my many colleagues who have contributed to this book. I am deeply grateful. I acknowledge in particular doctors, nurses, nursing auxiliaries, technicians, and caretakers of the Mostoles University Hospital, Madrid, where I carried out the first stage of my research.

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It is a pleasure to acknowledge the skilled work on human anatomy by professors Alberto Prats-Galino, Xavier Sala-Blanch, and Anna Puigdellívol Sánchez from the University of Barcelona and Anna Carrera at the University of Girona.

Many people were involved in various aspects of this project including text translation and revision (Fabiola Machés). I would like to acknowledge and thank them for their precious time, valuable suggestions, and encouragement during the various phases of the elaboration of this book.

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# Part I

# Human Peripheral Nerve

# Ultrastructure of Myelinated and Unmyelinated Axons

1

Miguel Angel Reina, Riánsares Arriazu Navarro, and Esther M. Durán Mateos

The macroscopic anatomy of peripheral nerves results from the hierarchic arrangement of nerve fibers formed by microscopic groups of motor and sensory neuronal cytoplasmic elongations known as axons [1–8]. The latter enable conduction of electrical impulses along their plasma membranes, as well as chemically mediated signal transduction throughout cytoplasmic organelles. Most peripheral nerves are mixed nerves containing efferent motor fibers, afferent sensory fibers, and sympathetic fibers. The initial segment of an axon (AIS) originates in the soma and is located between the cell body and the beginning of the myelin sheath. This site is a polarized structure containing proteins such as voltage-gated sodium channels (VGCs), which are responsible for producing the inward ionic flow that generates the action potential at the AIS. VCGs at the AIS, together with the linked spectrin–actin membrane cytoskeleton may function as a diffusion barrier preventing axonal proteins from leaking out of the neuron. Nerve fibers have two types of axons, myelinated and unmyelinated. Each myelinated nerve fiber consists of an axon covered by myelin sheaths produced by Schwann cells alternating with areas called nodes of Ranvier [1–4]. The latter are sites of discontinuity between successive myelin sheaths along the axon [5, 6]. Mechanisms regulating the production and distribution of myelin take place in an extremely tight compartment located between the plasma membranes of both neurons and Schwann cells [7]. An inner layer, or basal membrane, and an outer layer, known as the endoneurium, enclose each myelinated nerve fiber. The axon contains an extremely dense cytoplasm, with an estimated viscosity five times greater than that of water. Inside the cytoplasm are microtubules, neurofilaments, mitochondria, vesicles, cisterns of cytoplasmic reticulum, and lysosomes, whereas ribosomes and Golgi apparatus are present uniquely in the AIS [5, 6]. The external diameter of a myelinated axon measures between 2 and 18 μm, whereas its length varies remarkably, ranging from just a few millimeters to as long as 1 m [5, 6].

Schwann cells wrap around axons at regular intervals, leaving uncovered portions known as Ranvier nodes [7]. The internodal distance is the interval between Ranvier nodes, is occupied by alternating Schwann cells, and measures about 0.4–1.2 mm.

Membrane depolarization and repolarization of myelinated axons during the propagation of action potentials occur at the Ranvier nodes; here, the proportion of VGCs is greater than in other unmyelinated areas.

Unmyelinated axons are not enclosed within multilayered myelin sheaths [8]. Instead, a single Schwann cell appears at the center of axonal groups, emitting cytoplasmic prolongations that separate each of the surrounding unmyelinated axons. Here, groups of six to eight axons are held together and partially covered by simple, nonwrapping prolongations originating in a single Schwann cell. In addition, groups of unmyelinated axons contain bundles of collagen fibers that confer mechanical resistance to the axonal group. The diameter of unmyelinated axons measures about 0.1–3 μm (Figs. 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, 1.10, 1.11, 1.12, 1.13 and 1.14).

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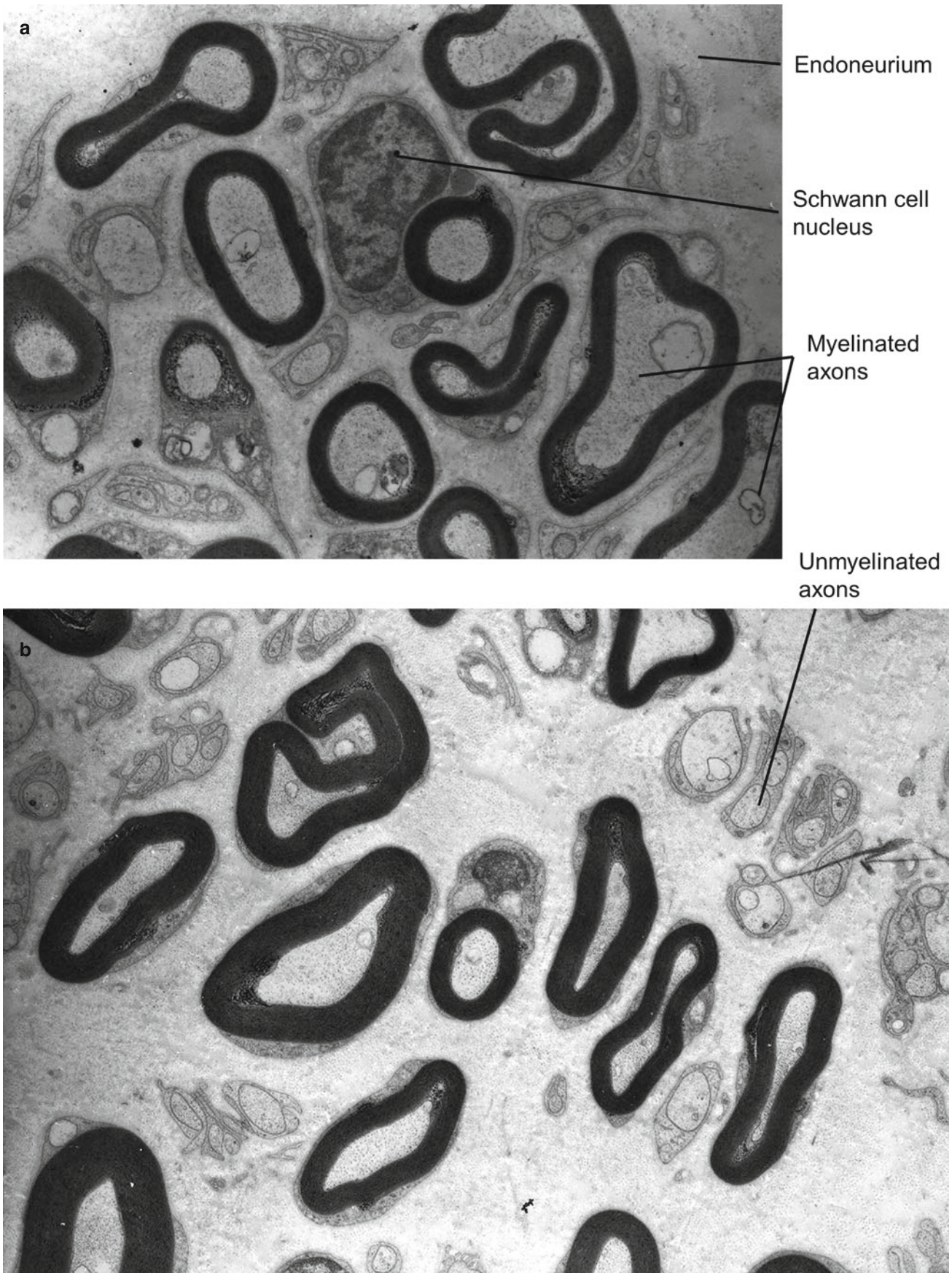


**Fig. 1.1** Axons inside fascicles of a sciatic nerve. Transmission electron microscopy, magnification: ×7,000 (**a**); ×3,000 (**b**)

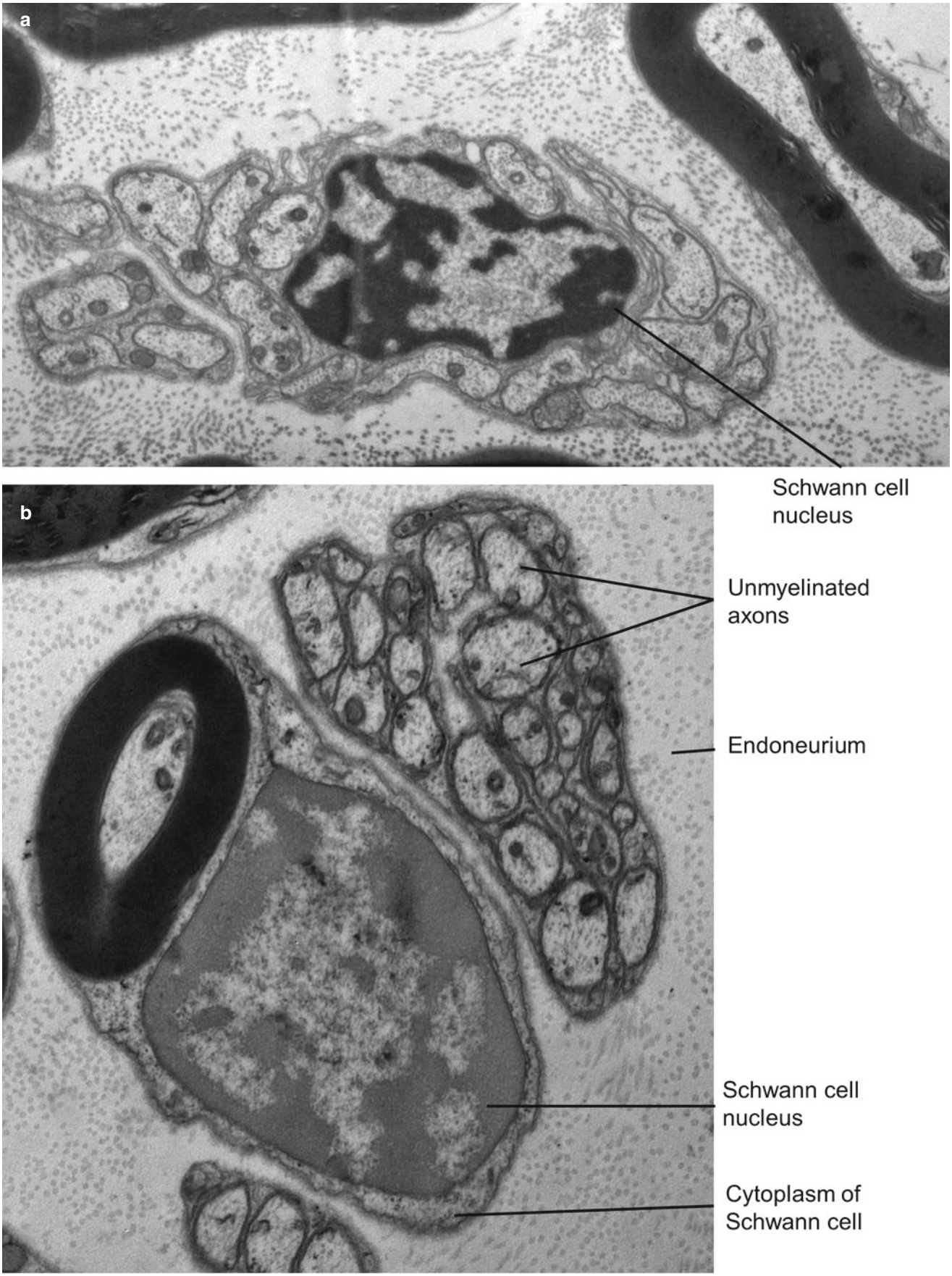


**Fig. 1.2** (**a**) Unmyelinated axon of a human nerve rootlet. (**b**) Myelinic axon surrounded by Schwann cells and an unmyelinated axon of a human nerve rootlet. Transmission electron microscopy, magnification: ×15,000 (**a**); ×25,000 (**b**)

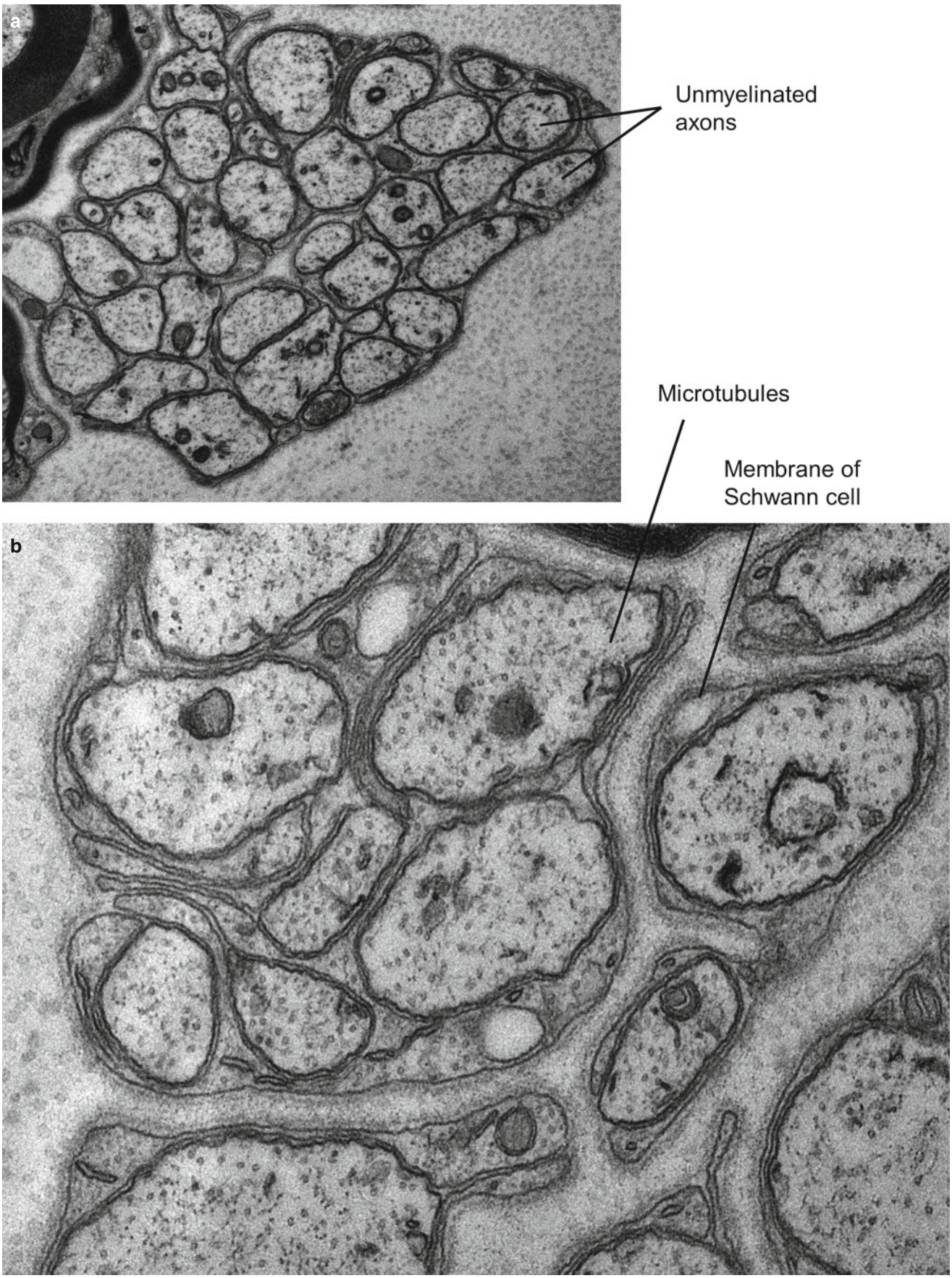


**Fig. 1.3** Unmyelinated axon of a human nerve rootlet. Transmission electron microscopy, magnification: ×30,000 (**a**); ×50,000 (**b**)

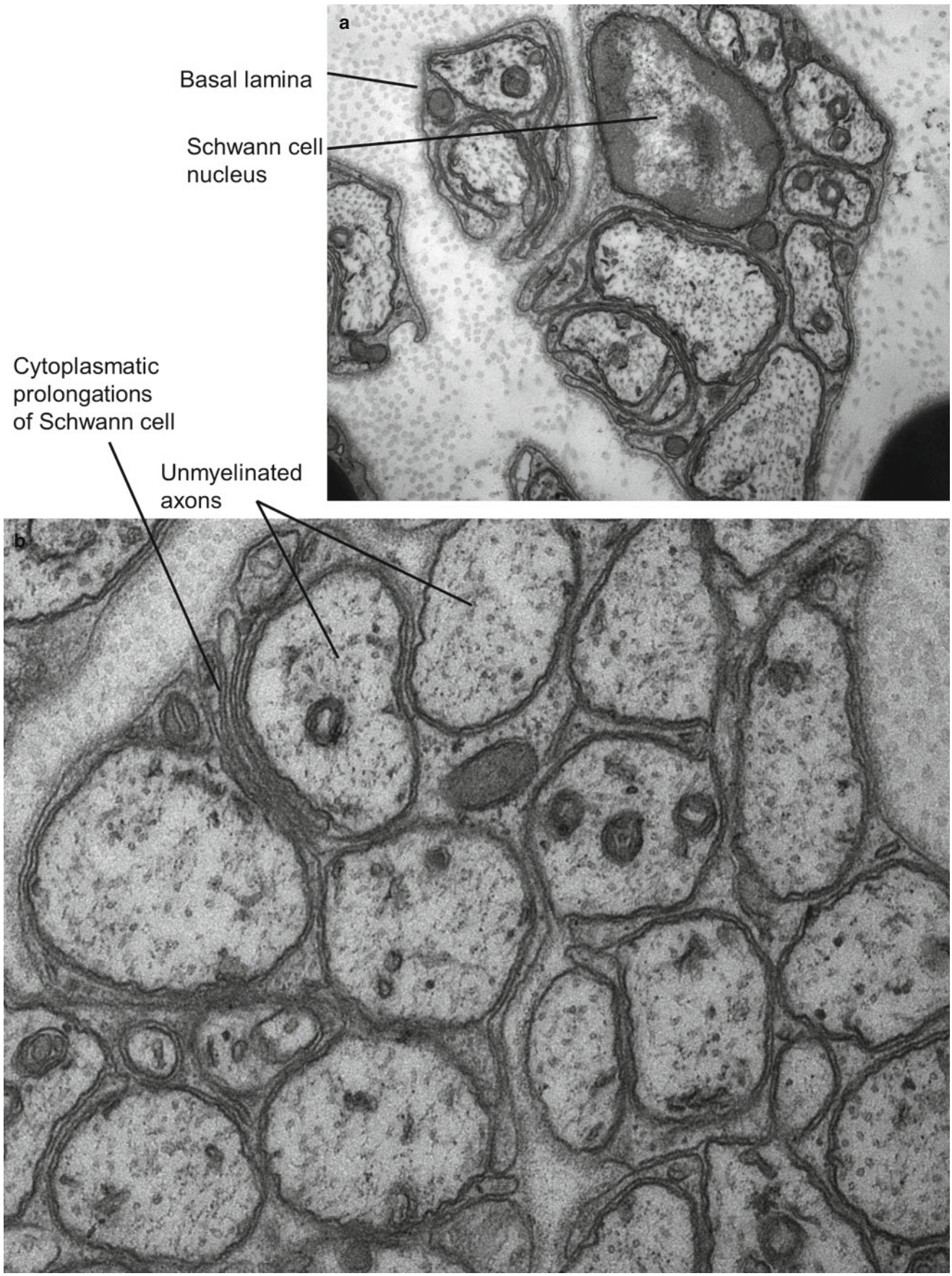


**Fig. 1.4** Unmyelinated axon of a human nerve rootlet. Transmission electron microscopy, magnification: ×40,000 (**a**); ×50,000 (**b**)

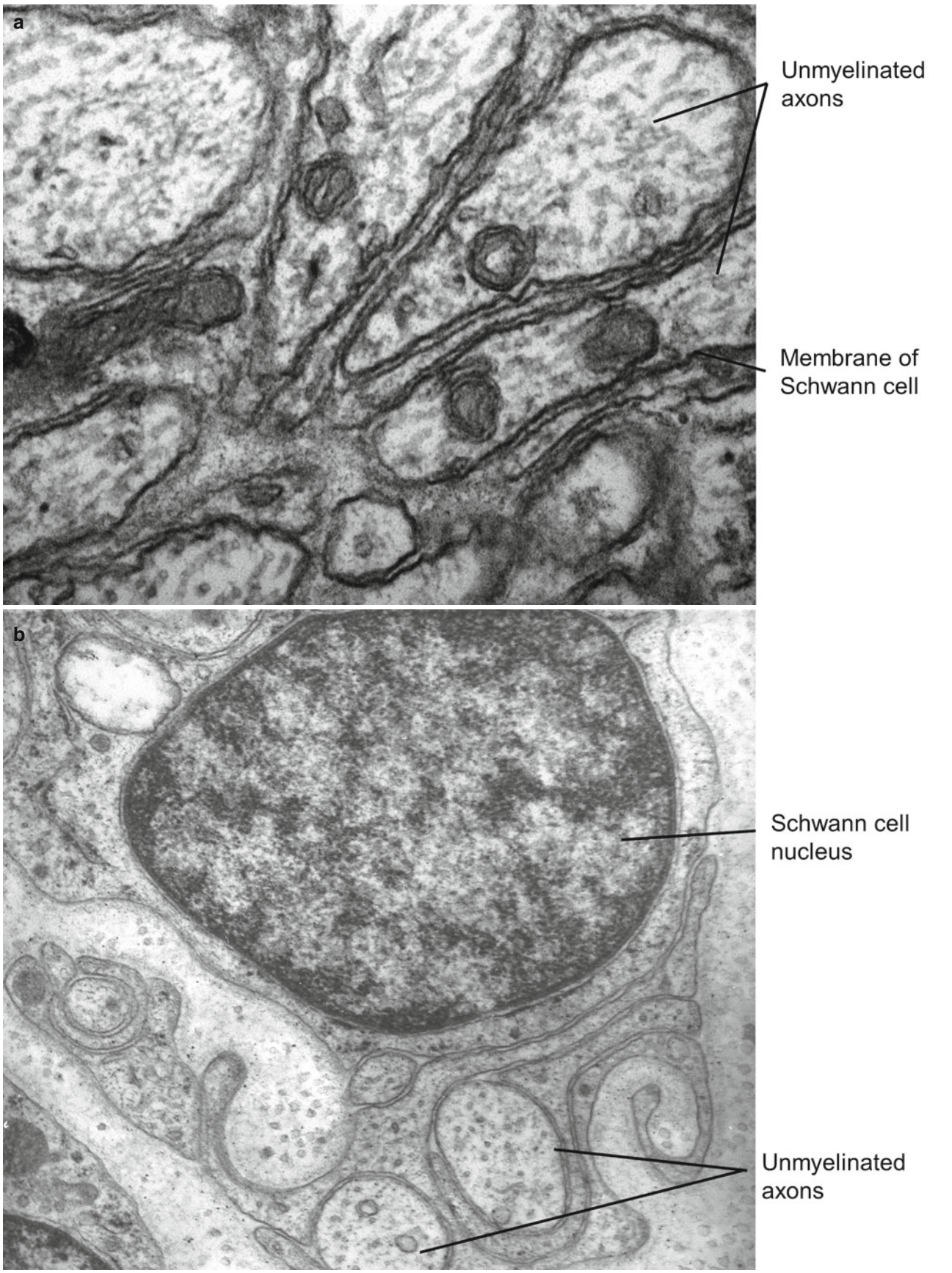


**Fig. 1.5** (**a**) Unmyelinated axon of a human nerve rootlet. (**b**) Unmyelinated axon of a sciatic nerve (From De Andrés et al. [4]; with permission) Transmission electron microscopy, magnification: ×100,000 (**a**); ×20,000 (**b**)

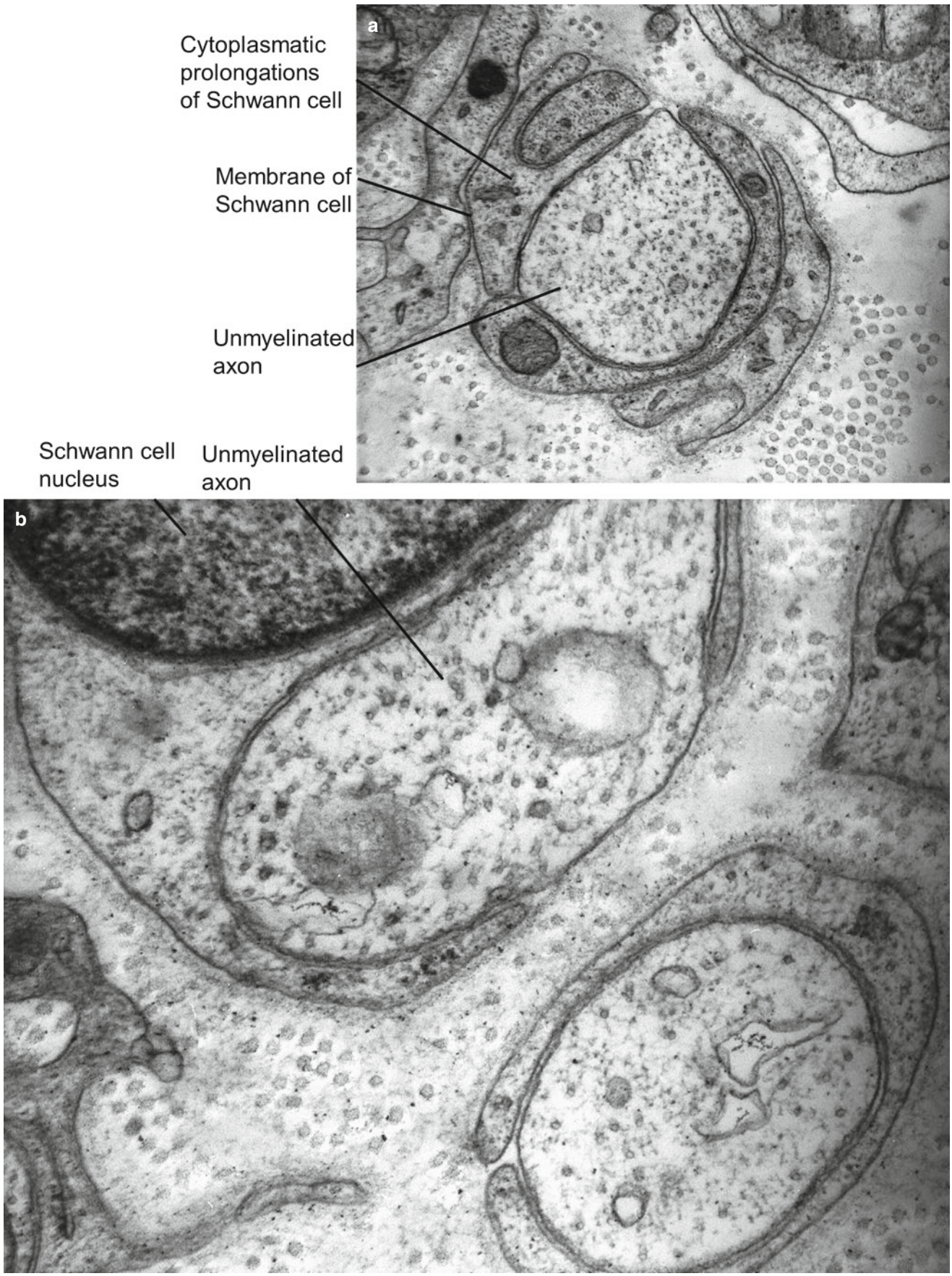


**Fig. 1.6** Unmyelinated axon of a sciatic nerve. Transmission electron microscopy, magnification: ×30,000 (**a**); ×30,000 (**b**)

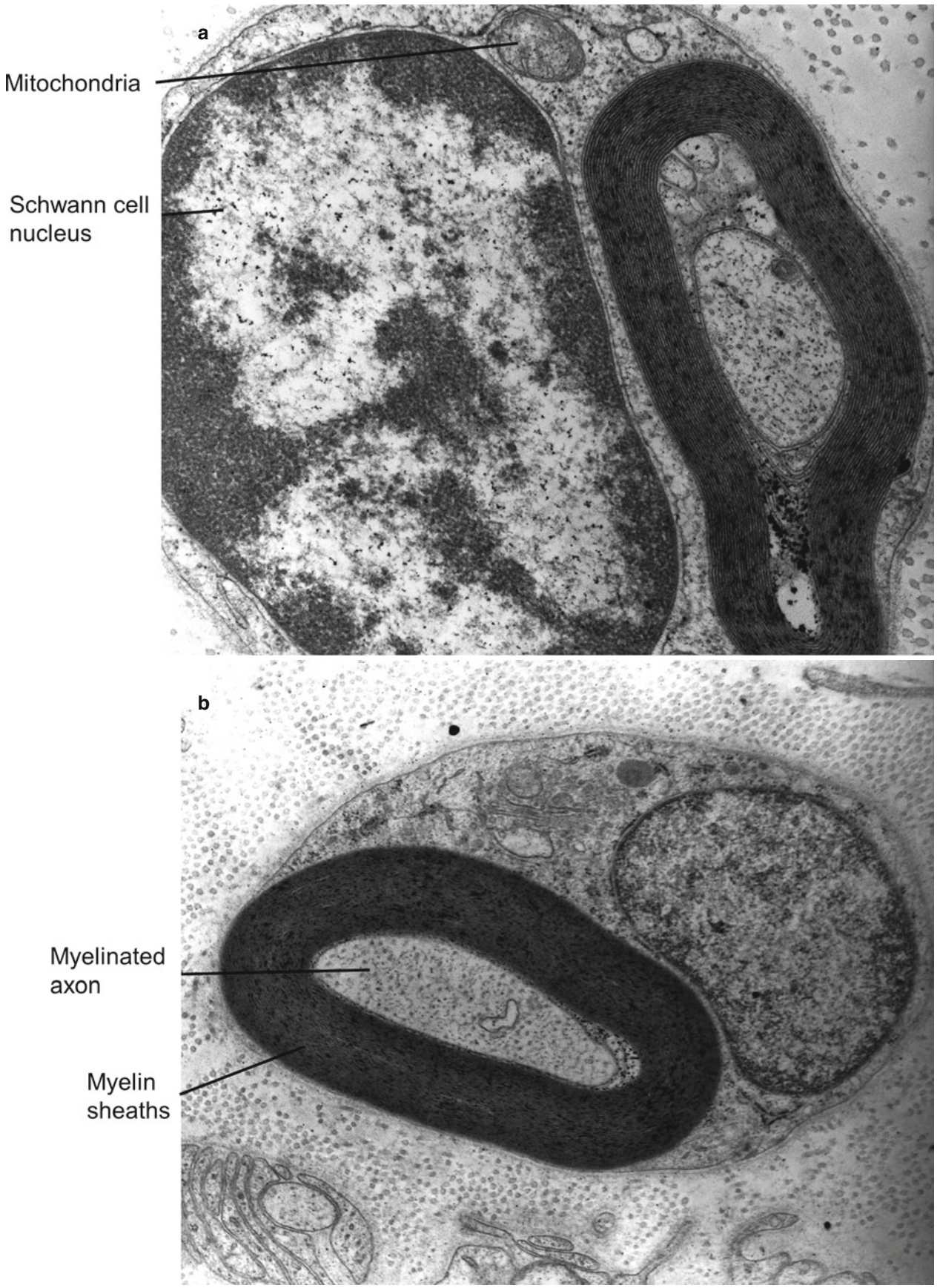


**Fig. 1.7** Myelinated axon of a sciatic nerve. Transmission electron microscopy, magnification: ×20,000 (**a**); ×12,000 (**b**) (Panel **b** from Reina et al. [1]; with permission)

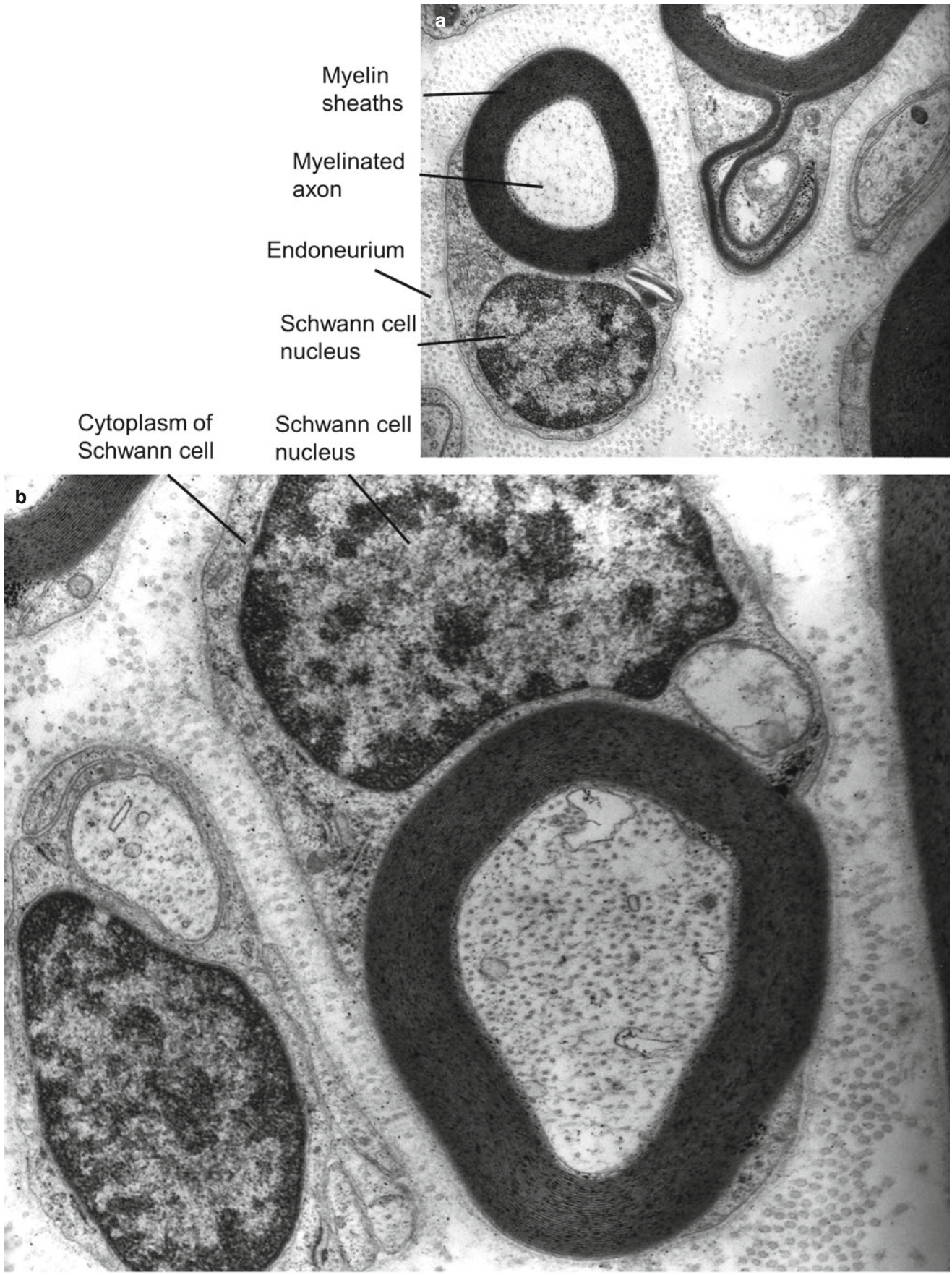


**Fig. 1.8** Myelinated axon of a sciatic nerve. Transmission electron microscopy, magnification: ×12,000 (**a**); ×12,000 (**b**)


**Fig. 1.9** Myelinated axon of a sciatic nerve. Transmission electron microscopy, magnification: ×7,000 (**a**); ×25,000 (**b**)