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Oxford Textbook of Neurological Surgery

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Oxford Textbook of

Neurological Surgery

Oxford Textbooks in Surgery

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Oxford Textbook of

Neurological Surgery

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Series Preface

This is a new development in surgical publishing; the first two editions of the Oxford Textbook of Surgery are to be replaced by a series of specialty-specific textbooks in surgery. This change was precipitated by the ever-increasing size of a single textbook of surgery which embraced all specialties (the second edition of the Oxford Textbook of Surgery was three volumes), and a decision to adapt the textbooks to meet the needs of the audience; firstly, to suit the requirements of Higher Surgical trainees and, secondly, to make it available online.

Thus, we have produced a key book to deal with the fundamentals of surgery, such as Anatomy, Physiology, Biochemistry, Evaluation of Evidence, and so forth. Then there are to be separate volumes covering individual specialties, each appearing as an independent textbook and available on Oxford Medicine Online.

It is planned that each textbook in each specialty will be independent although there obviously will be an overlap between different specialties and, of course, the core book on Fundamentals of Surgery will underpin the required scientific knowledge and practice in each of the other specialties.

This ambitious programme will be spread over several years, and the use of the online platform will allow for regular updates of the different textbooks.

Each textbook will include the proposed requirements for training and learning as defined by the specialist committees (SACs) of surgery recognized by the four Colleges of Surgery in Great Britain and Ireland, and will continue to be applicable to a global audience.

This ambitious programme will be spread over several years, and the use of the online platform will allow for regular updates of the different textbooks.

When completed, the Oxford Textbooks in Surgery series will set standards for a long time to come.

Professor Sir Peter J. Morris
Nuffield Professor of Surgery Emeritus, and former Chairman of the Department of Surgery and Director of the Oxford Transplant Centre, University of Oxford and Oxford Radcliffe Hospitals, UK

Forewords

The *Oxford Textbook of Neurological Surgery* is a new book complementing the Oxford Textbooks in Surgery series. It is arguably the first British-led comprehensive textbook covering the breadth of neurological surgery since *Northfield's Surgery of the Central Nervous System*.

Although the book was conceived and led from the United Kingdom, it has an extensive international contribution and will be of value to specialists from all countries.

The book bridges the gap between short handbook-type texts and the large encyclopaedic multivolume tomes. It is suited to junior and senior neurosurgical trainees and consultants, and will also be useful to specialists from other disciplines. In addition, it will be of immense benefit to those studying for the UK Intercollegiate Neurosurgical Examination, the European examination, and equivalent examinations in other continents. It is written in such way as to emphasize the clinical implications of the science.

The book is divided into 20 main sections with 99 chapters, 1000 pages in print, and over 1000 figures and tables. The chapters are carefully arranged such that it can be read from cover to cover or used as a reference for specific topics, given the comprehensive index. Each chapter follows a uniform format with abstract and key words, followed by comprehensive coverage of the topic illustrated by clear multicoloured figures.

The hard-copy print edition is complemented by an online version, which provides an alternative format to enabling instant access to specific topics.

The ability to update at the proof stage means the book is up-to-date in covering recent advances; for example, the results of clinical trials.

I congratulate the authors on bringing together experts from all neurosurgical subspecialties and from all across the globe to deliver a book that is clearly laid out, readable, and well-illustrated. I am sure it will find its place as a reference book on the bookshelves of neurosurgeons across the globe.

Franco Servadei

The past four decades have seen advances on a scale and pace that have made the practice of neurosurgery almost unrecognizable in comparison to the specialty in which I trained. The dawning in the 1970s of microsurgery and cross-sectional imaging, along with advances in pre- and perioperative care, sparked technological and technical developments that reinvented concepts of what is possible several times over. Specialization became necessary to take full advantage of the new opportunities to advance patients' outcomes and neurosurgeons were spurred to accumulate the dedicated, detailed knowledge, skills, and experience that drove the specialty forward and made it increasingly complex and diverse.

The editors of the *Oxford Textbook of Neurological Surgery* have taken on a substantial challenge: to provide, in a single, comprehensive volume, the knowledge that spans the practice of modern neurosurgery. Alongside this sheer breadth are integrated two critical perspectives: a rigorous understanding of basic science and the subtlety of neurosurgical operative practice.

It succeeds in filling a gap in the neurosurgical literature: a single volume that provides a thorough review of neurological surgery for trainee and trained surgeons alike. Its approach is forward-looking, highlighting the importance of basic and clinical research and evidence-based medicine. Safe and successful neurosurgery will increasingly require deep anatomical knowledge, clinical judgement, and high levels of technical skill, tied to an ability to synthesize an ever-growing and complex literature into reasoned practice.

UK neurosurgery has a proud history. Modern neurological surgery dawned in Scotland (Glasgow) in 1879 and the Society of British Neurological Surgeons is one of the oldest national societies in the world. But its perspective has been and remains broad, engaging colleagues in the worldwide community of neurosurgeons that transcends shifting national, political boundaries. Reflecting this, although the book is undoubtedly grounded in UK neurosurgery, the editors have successfully drawn in some of the most prolific and experienced surgeons and insightful scientists from around the world. As a result, the *Oxford Textbook of Neurological Surgery* provides an invaluable companion to neurosurgeons, from their earliest years of training into subspecialty experience and consultant practice. It will become the definitive single volume textbook for those who treat surgical disorders of the nervous system in the United Kingdom and around the world.

Sir Graham Teasdale

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Symbols and abbreviations

Ω	omega
α	alpha
β	beta
δ	gamma
μg	micrograms
AAA	asleep-awake-asleep
AAICH	anticoagulation-associated intracerebral haemorrhage
AANS	acute and chronic settings
ABC	aneurysmal bone cyst
ABI	auditory brainstem implants
ABR	auditory brainstem responses
AC	anterior and posterior commissure (also arachnoid cyst)
ACA	anterior cerebral artery
ACD	anterior cervical discectomy
ACPP	atypical choroid plexus papilloma
ADC	apparent diffusion coefficient
ADI	atlantodental interval
ADL	activities of daily living
ADNFLE	autosomal-dominant nocturnal frontal lobe epilepsy
ADPKD	autosomal dominant polycystic kidney disease
AED	antiepileptic drug
AF	atrial fibrillation
AGNIR	Advisory Group on Non-ionising Radiation
AICA	anterior inferior cerebellar artery
AIDS	acquired immunodeficiency syndrome
AIP	aryl hydrocarbon receptor-interacting protein
AIS	Abbreviation Injury Score (*also* ASIA Impairment Scale)
ALI	acute lung injury
ALIF	anterior lumbar interbody fusion
ALL	acute lymphatic leukaemia
ALL	anterior longitudinal ligament
AP	anteroposterior
ASA	American Society of Anesthesiologists
ASA	anterior spinal artery
ASIA	American Spinal Injuries Association
ASPECTS	Alberta Stroke Programme Early CT Score
AT	anaplastic transformation
ATA	anterior temporal artery
ATIII	antithrombin III
ATLS	advance trauma life support
ATRT	atypical teratoid rhabdoid tumour
AVF	arteriovenous fistula
AVM	arteriovenous malformation
AZ	Annulus of Zinn
BAEP	brainstem auditory evoked potentials
BBB	blood–brain barrier
BECTS	benign epilepsy with centrotemporal spikes
BIS	bispectral index
BMD	bone mineral density
BMI	body mass index
BOLD	blood oxygen level dependent
BP	blood pressure
BRAT	Barrow Ruptured Aneurysm Trial
BTF	Brain Trauma Foundation
CA	cerebral autoregulation
CAA	cerebral amyloid angiopathy
CAD	coronary artery disease
CAMS	cerebrofacial metameric arteriovenous syndromes
CAPECTH	craniectomy-associated progressive extra-axial collections with treated hydrocephalus
CAR	cerebral autoregulation
CAS	carotid angioplasty and stenting
CBF	cerebral blood flow
CBV	cerebral blood volume
CCA	common carotid artery
CCM	cerebral cavernous malformations
CDC	Centers for Disease Control
CDK	cyclin dependent kinases
CFAM	cerebral function analysing monitor
CHF	congestive heart failure
CHLA	Children's Hospital Los Angeles
CISS	Constructive Interference in Steady State
CM	cavernous malformations
CM	central myelin
CMAP	compound motor action potential
$CMRO_2$	cerebral metabolic rate of oxygen consumption
CN	cranial nerve
CNS	central nervous system (also Congress of Neurological Surgeons)
COPD	chronic obstructive pulmonary disease
COSS	Carotid Occlusion Surgery Study
CPA	cerebellopontine angle
CPC	choroid plexus carcinoma
CPH	choroid plexus hyperplasia
CPP	cerebral perfusion pressure (also choroid plexus papilloma)
CPP	choroid plexus papilloma
CPT	choroid plexus tumour

CRF	corticotrophin factor
CRH	corticotrophin-releasing hormone
CRP	C-reactive protein
CRPS	complex regional pain syndrome
CRW	Cosman-Roberts-Wells
CSF	cerebrospinal fluid
CSW	cerebral salt wasting
CSWS	cerebral salt wasting syndrome
CT	computed tomographic
CTA	computed tomography angiography
CTP	cerebellar tonsillar prolapse
CTS	carpal tunnel syndrome
CTV	clinical target volume
CUSA	cavitron ultrasonic surgical aspirator
DBS	deep brain stimulation
DEBS	direct electrical brain stimulation
DES	drug-eluting stents
DESD	detrusor external sphincter dyssynergia
DEXA	dual-energy X-ray absorptiometry
DI	diabetes insipidus
DIND	delayed ischaemic neurological deficits
DISH	diffuse idiopathic skeletal hyperostosis
DLGG	diffuse low-grade gliomas
DNP	dynamic nuclear polarization
DNT	dysembryoplastic neuroepithelial tumours
DPG	diffuse pontine glioma
DRG	dorsal root ganglion
DRIFT	Drainage, Irrigation and Fibrinolytic Therapy
DSA	digital subtraction angiography
DSB	double-strand break
DTI	diffusion tensor imaging
DVA	deep venous anomaly
DVA	developmental venous anomaly
DVT	deep vein thrombosis
DWI	diffusion-weighted imaging
DWMH	deep white matter hyperintensities
DXA	dual X-ray absorbitometery
ECA	external carotid artery
ECG	electrocardiogram
ECoG	electrocorticography
EDF	elongation derotation flexion
EDL	extensor digitorum longus
EEA	endoscopic endonasal approach
EEG	electroencephalography
EGFR	epidermal growth factor receptor
EIEE	early infantile onset epileptic encephalopathies
ELISA	enzyme-linked immunosorbent assay
EMA	epithelial membrane antigen
EMG	electromyography
ENT	ear, nose, and throat
EOIS	early onset idiopathic scoliosis
EOR	extent of resection
EORTC	European Organization for Research and Treatment of Cancer
EP	evoked potential
EPC	epilepsia partialis continua
ES	ethmoid sinus
ERG	Electroretinogram
ES	Ewing's sarcoma
ESO	European Stroke Organisation
ESR	erythrocyte sedimentation rate
ET	essential tremor
ETT	endotracheal tube
ETV	endoscopic third ventriculostomy
EVD	external ventricular drain
EZ	epileptogenic zone
FA	fractional anisotropy
FCD	focal cortical dysplasias
FCU	flexor carpi ulnaris
FD	fibrous dysplasia
FDA	Food and Drug Administration
FEF	frontal eye field
FES	functional electric stimulation
FFP	fresh frozen plasma
FGN	French Glioma Network
FIESTA	fast imaging in steady state
FIPA	familial isolated pituitary adenoma
FLAIR	fluid attenuated inversion recovery
FLE	frontal lobe epilepsy
FM	Foramen of Monro
FSH	follicle-stimulating hormone
FSU	functional spinal unit
FTT	failure to thrive
FV	flow velocities
FZS	fronto-zygomatic suture
GABA	gamma aminobutyric acid
GAF	Global Assessment of Function
GCS	Glasgow Coma Scale
GCT	germ cell tumours (*also* granular cell tumour)
GFAP	glial fibrillary acid protein
GFR	glomerular filtration rate
GH	growth hormone
GHIH	growth hormone-inhibiting hormone
GHRH	growth hormone release hormone
GI	gastrointestinal
GMFM	Gross Motor Function Measure
GSPN	greater superficial petrosal nerve
GTCS	generalized tonic-clonic seizures
GTR	gross total resection
GTV	gross tumour volume
GW	gliadel wafers
H&E	haematoxylin and eosin
HBO	hyperbaric oxygen
HDDST	high-dose dexamethasone suppression tests
HGG	high-grade glioma
HHT	hereditary haemorrhagic telangiectasia
HIF	hypoxia inducible factor
HIFU	high-intensity focused ultrasound
HIV	human immunodeficiency virus
HLA	human leukocyte antigen
HMSN	hereditary motor, and sensory neuropathy
HO	heterotrophic ossification
HPA	hypothalamic-pituitary axis
HPC	haemangiopericytoma
HR	homologous recombination

HRQOL	health-related quality of life
HS	hippocampal sclerosis
HS	hypertonic saline
HSV	herpes simplex virus
HU	Hounsfield units
IA	intra-arterial
IAC	internal auditory canal
IAM	internal auditory meatus
IBE	International Bureau for Epilepsy
ICA	inferior cerebellar artery (also internal carotid artery)
ICA	internal carotid arteries
ICBP	infraclavicular brachial plexus
ICE	ifosfamide, carboplatin, and etoposide
ICH	intracerebral haemorrhage
ICP	intracranial pressure
ICU	intensive care unit
IFOF	inferior fronto-occipital fasciculus
IJV	internal jugular vein
ILAE	International League Against Epilepsy
IO	inferior oblique
IOF	inferior orbital fissure
IOM	Intraoperative monitoring
IPG	implantable pulse generator
IPG	implanted battery-operated pulse generators
IPSS	inferior petrosal vein sampling
IR	inferior rectus
IR	iterative reconstruction
ISAT	International Subarachnoid Aneurysm Trial
ISCoS	International Spinal Cord Society
ISNCSCI	International Standards for Neurological Classification of Spinal Cord Injury
ITB	intrathecal baclofen
IVC	inferior vena cava
IVP	intraventricular pressure
JET	Japanese EC-IC Bypass Trial
KOLT	Kendrick object learning test
kPa	kilopascal
KPS	Karnofsky Performance Status
LCH	Langerhans cell histiocytosis
LDD	L'hermitte-Duclos disease
LDDST	low-dose dexamethasone suppression test
LDL	low-density lipoprotein
LDM	limited dorsal myeloschisis
LFS	Li-Fraumeni syndrome
LG	lacrimal gland
LGG	low-grade glioma
LH	luteinizing hormone
LINAC	linear accelerator
LMN	lower motor neuron
LMWH	low molecular weight heparin
LOC	level of consciousness
LOH	loss of heterozygosity
LOIS	late onset idiopathic scoliosis
LOR	line of response
LOVA	longstanding overt ventriculomegaly in adults
LP	levator palpebrae
LP	lumbar puncture
LR	lateral rectus
LR	Lindegaard ratio
LSO	lumbar sacral orthosis
LSR	lateral spread responses
MAC	minimal alveolar concentration
MAP	mean arterial pressure
MC	Meckel cave
MCA	middle cerebral artery
MCD	malformation of cortical development
MDT	multidisciplinary team
MEG	magnetoencephalography
MEP	minimally endoscopic procedures
MEP	motor evoked potential
MHC	major histocompatibility complex
MI	myocardial infarction
MIP	maximum intensity projection
MIT	minimally invasive techniques
MLF	medial longitudinal fasciculus
MM	multiple myeloma
MMD	moya moya disease
MMS	moya moya syndrome
MMSE	mini-mental state examination
MND	motor neurone disease
MOG	myelin oligodendrocyte glycoprotein
MPBT	malignant paediatric brain tumours
MPNST	malignant peripheral nerve sheath tumours
MR	magnetic resonance
MR	medial rectus
MRA	magnetic resonance angiography
MRA	MR-angio
MRC	Medical Research Council
MRI	magnetic resonance imaging
MRM	magnetic resonance myelography
MRN	magnetic resonance neurography
MRS	magnetic resonance spectroscopy
MRSA	methicillin-resistant Staphylococcus aureus
MRV	magnetic resonance venography
MS	multiple sclerosis
MSH	melanocyte-stimulating hormone
MTG	middle temporal gyrus
MTLE	mesial temporal lobe epilepsy
MTT	mean transit time
MUAP	motor unit action potential
MVA	motor vehicle accidents
MVC	motor vehicle collisions
MVD	microsurgical vascular decompression
Na+	sodium
NAA	N-acetyl aspartate
NASCIS	National Acute Spinal Cord Injury Studies
NCS	nerve conduction studies
NeuN	neuronal nuclei
NFPA	non-functioning pituitary adenomas
NHEJ	non-homologous end-joining
NHL	non-Hodgkin's lymphoma
NICE	National Institute of Clinical Excellence
NIRS	near infrared spectroscopy
NLI	neurological level of injury
NMDA	N-methyl-D-aspartate
NMS	non-motor symptoms

NOAC	new oral anticoagulants
NOS	not otherwise specified
NPH	normal pressure hydrocephalus
NPSA	National Patient Safety Agency
NPUAP	National Pressure Ulcer Advisory Panel
NSAID	non-steroidal anti-inflammatory drug
OC	optic canal
OCR	optico-carotid recesses
OCT	optical coherence tomography
ODI	Oswestry Disability Index
OEF	oxygen extraction fraction
OLE	occipital lobe epilepsy
OLF	ossification of the ligamentum flavum
ON	optic nerve
OPG	optic pathway glioma
OPLL	ossification of the posterior longitudinal ligament
OS	overall survival
OSA	obstructive sleep apnoea
PA	pilocytic astrocytoma
PAR	protease-activated receptors
PBI	penetrating brain injury
PBT	paediatric brain tumour
PCA	posterior cerebral artery
PCC	prothrombin complex concentrate
PCNSL	primary central nervous system lymphoma
PCR	polymerase chain reaction
PCV	procarbazine, CCNU, vincristine
PD	Parkinson's disease (also proton density)
PDGFR	platelet-derived growth factor receptor
PE	preoperative embolization
PE	pulmonary embolism
PEDI	Pediatric Evaluation of Disability Inventory
PEEK	poly-ether-ether-ketone
PEEP	positive end-expiratory pressure
PEG	percutaneous endoscopic gastrostomy
PET	positron emission tomography
PFO	patent foramen ovale
PFS	progression-free survival
PI	pelvic incidence
PICA	posterior inferior cerebellar artery
PIH	prolactin-inhibiting hormone
PIOL	primary intraocular lymphoma
PLL	posterior longitudinal ligament
PML	progressive multifocal leukoencephalopathy
PNET	primitive neuroectodermal tumour
PONV	postoperative nausea and vomiting
PPTID	pineal parenchymal tumours of intermediate differentiation
PRH	prolactin-releasing hormone
PSA	posterior spinal arteries
PSO	pedicle subtraction osteotomy
PT	pelvic tilt (*also* prothrombin time)
PTA	pure-tone audiogram
PTH	post-traumatic hydrocephalus
PTPR	papillary tumour of the pineal region
PTS	post-traumatic seizures
PTSD	post-traumatic stress disorder
PTT	partial thromboplastin time
PTV	planning target volume
PVA	poly-vinyl-alcohol
QoL	quality of life
QOLIBRI	Quality of Life after Brain Injury
RA	rheumatoid arthritis
RANKL	receptor activator of NF-KB ligand
RANO	Response Assessment in Neuro-Oncology
RAPD	relative afferent pupil defect
RCC	renal cell carcinoma
RCN	Rare Cancer Network
RCT	randomized clinical trials
REM	rapid eye movement
REZ	root entry zone
RF	rheumatoid factor
RNFL	retinal nerve fibre layer
RT	radiation therapy
RT	resistance in the tube
RVAD	rib-vertebral-angle difference
SAH	subarachnoid haemorrhage
SARS	sacral anterior nerve root stimulator
SBP	supraclavicular brachial plexus
SCA	superior cerebellar artery
SCA	superior cerebellar artery
SCAVM	spinal cord arteriovenous malformations
SCI	spinal cord injury
SCID	severe-combined immunodeficiency disease
SCM	strap muscles
SCO	spindle cell oncocytoma
SCPP	spinal cord perfusion pressure
SDAVF	spinal dural arteriovenous fistula
SDR	selective dorsal rhizotomy
SDS	speech discrimination score
SEA	spinal epidural abscess
SEEG	stereoencephalography
SEER	Surveillance Epidemiology and End Results
SEGA	subependymal giant cell astrocytomas
SEP	Somatosensory evoked potential
SESH	spontaneous epidural spinal haemorrhage
SFT	solitary fibrous tumour
SGCT	subependymal giant cell tumour
SIADH	syndrome of inappropriate antidiuretic hormone
SIVMS	Scottish Intracranial Vascular Malformation Study
SLE	systemic lupus erythematous
SLF	superior longitudinal fasciculus
SMA	supplementary motor area
SNAP	sensory nerve action potential
SNO	Society for NeuroOncology
SNUC	sinonasal undifferentiated carcinoma
SO	superior oblique
SOF	superior orbital fissure
SOM	spheno-orbital meningiomas
SOV	superior ophthalmic vein
SPECT	single photon emission computed tomography
SPES	single pulse electrical stimulation
SPN	selective peripheral neurotomy
SPV	superior petrosal venous
SR	superior rectus

SSFP	steady state free precession
SSI	surgical site infection
SSMA	supplementary sensorimotor area
SSS	superior sagittal sinus
SST	Short Synacthen Test
STA	superficial temporal artery (*also* superior thyroid artery)
STASCIS	Surgical Treatment of Acute Spinal Cord Injury Study
STG	superior temporal gyrus
STIR	short tau inversion recovery
STR	subtotal resection
SUDEP	sudden unexplained death in epilepsy
SUNCT	short-lived, unilateral neuralgic headache with conjunctival injection and tearing
SVA	sagittal vertical axis
SVM	spinal vascular malformation
SWI	susceptibility weighted imaging
TBI	traumatic brain injury
TCD	transcranial Doppler
TCGA	The Cancer Genome Atlas
TF	tissue factor
TFPI	tissue factor pathway inhibitor
TIVA	total intravenous anaesthesia
TLE	temporal lobe epilepsy
TLSO	thoracolumbar sacral orthosis
TMG	transmural pressure gradient
TMS	tumefactive multiple sclerosis
TN	trigeminal neuralgia
TOF	time of flight
TORCH	Toxoplasmosis, Other (syphilis, varicella-zoster, parvovirus B19), Rubella, Cytomegalovirus (CMV), and Herpes infections
TREZ	trigeminal root entry zone
TRH	thyroid-releasing hormone (*also* thyrotropin-releasing hormone)
TSC	tuberous sclerosis complex
TSH	thyroid-stimulating hormone
TT	thrombin time
TTM	targeted temperature management
TTP	time to peak
TZ	transitional zone
UH	unfractionated heparin
UMN	upper motor neuron
UMNL	upper motor neurone lesions
VA	vertebral artery
VAD	ventricular access device
VAE	venous air embolism
VASO	vascular space occupancy
VBA	vertebrobasilar artery
VDE	velocity of diametric expansion
VEGF	vascular endothelial growth factor
VEP	visual evoked potential
VGAM	vein of Galen malformations
VGPN	vago-glossopharyngeal neuralgia
VHL	Von Hippel-Lindau
VMAT	volumetric modulated arc therapy
VNS	vagus nerve stimulation
VP	vancomycin powder
VP	ventriculoperitoneal
VRE	vancomycin-resistant enterococci
VS	vestibular schwannoma (also ventral striatum)
VTE	venous thromboembolism
vWF	von Willebrand factor
WBC	white blood cell
WBRT	whole-brain radiation therapy
WFNS	World Federation of Neurosurgical Societies
WFSBP	World Federation of Societies of Biological Psychiatry
WHO	World Health Organization
YBOCS	Yale-Brown Obsessive-Compulsive Scale

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SECTION 1

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The history of neurosurgery

Eleni Maratos and Henry Marsh

Introduction

The history of neurosurgery falls naturally into the premodern era, where it is essentially the history of surgery to the skull and of head injuries, and the modern era, where it is the history of surgery to the brain itself, made possible by cerebral localization theory, antisepsis, and anaesthesia, all of which developed in the nineteenth century.

The first known neurosurgical procedures were skull trephines, seemingly carried out on both the living and the dead. It is unclear whether these were performed for therapeutic or ritualistic reasons. There are many trepanned skulls dating back thousands of years to the Neolithic era, and perhaps to even earlier, from sites all over the world.

Ancient Egypt

The earliest neurosurgical writings can be traced to Ancient Egypt and have been preserved in the Edwin Smith Papyrus that dates from *c.*1600 BC. This is the first time that the management of head injuries was based on rational scientific method rather than magic. In a style that is highly reminiscent of modern case reports, the first ten cases focus on head wounds and also contain the earliest known reference to the brain itself (as opposed to the skull), which describes a 'convoluted structure like ripples that happen in copper through smelting'. The cases vividly describe a methodical approach—first ascertaining the depth of the injury and whether there is an underlying skull fracture or exposed brain, and then advocating different management strategies according to the findings. The papyrus has been translated and reproduced by the National Institutes of Health and can be studied online (https://ceb.nlm.nih.gov). As well as the earliest known advice on head injury management, the Edwin Smith Papyrus also contains the first references to spinal immobilization in order to prevent further injury.

Ancient Greece and Byzantium

Hippocrates (460–370 BC) wrote extensively on head injuries in *De capitis vulneribus* (*On Head Wounds*). His management strategy was almost exclusively based on classifying the fracture rather than on the clinical state of the patient. He described five categories of skull fracture, including contre-coup injuries. On head injuries, he wrote *'nullum capitis vulnus contemnendum est'* (no head injury should be considered trivial). His writings were not confined to head injury and he is also credited with the first description of a subarachnoid haemorrhage:

> . . . when persons in good health are suddenly seized with pains in the head and straight away are laid down speechless and breath with stertor they die in seven days unless fever comes on.

He also described contralateral convulsions associated with brain injury; he can therefore perhaps be credited with being the first doctor to describe cerebral localization.

The Alexandrian school introduced formal anatomy dissection in approximately 300 BC. It was at this time that Herophilus began to develop the anatomic nomenclature that we use today (see **Fig. 1.1**). He identified that nerves and tendons were indeed different structures, contrary to what the Egyptians had thought, and he also was the first to describe the anatomy of the ventricles and the venous sinuses. The confluence of the sinuses, of course, still bears his name 'torcula (wine press) Herophili'. He also described the pen nib or 'calamus scriptorius' at the base of the fourth ventricle 'αναγλυφη της χαλαμης' and the choroid plexus (named after its resemblance to the vessels of the placenta).

Celsus, who lived from 25 BC to 50 AD, was the first to describe inflammation (*rubor, dolor, tumor*) and also wrote about extradural haemorrhage, hydrocephalus, trigeminal neuralgia, and spinal fractures. He advocated craniotomy only as a last resort in head injury and described the technique of drilling holes and connecting them up with a hammer and chisel with a protective blade. In another early account of cerebral localization, he advised operating on the side with the greatest pain.

Galen 129–200 AD

With Galen came the encephalocentric model of science and medicine, where the brain was recognized as the seat of intelligence and voluntary movement. He identified the pia (as different from the dura mater), the corpus callosum, the ventricles (alongside Herophilus), and the pineal and pituitary glands. He described the aqueduct of

Fig. 1.1 Herophilus of Chalcedon (*c.* 330–260 BC), a Greek doctor who practised in Alexandria. Here he is seen depicted in discussion with Erasistratus of Ceos.
Wellcome Collection

Sylvius and the foramen of Monro before the anatomists whose names they now possess. He made other significant contributions to neuroscience by identifying that transecting the spinal cord leads to loss of function below the level of the lesion, and he also described what we now call Brown-Séquard syndrome. In addition, he noted that recurrent laryngeal nerve injuries led to hoarse 'voices' in his experimental dogs. He also advocated elevating depressed skull fractures and using irrigation to reduce the heat created by trephining. His teachings were accepted, largely unquestioned, for 1500 years.

During mediaeval times (750–1200 AD) most innovative medical writing came from the Islamic and Arabic worlds, which also kept the Hippocratic and Galenic teachings alive. It was during this time that traditional bedside teaching was established.

The beginning of the scientific era

The sixteenth and seventeenth centuries were remarkable for the advances in all aspects of science and philosophy. Anatomical dissection of cadavers was already practised in mediaeval Europe before Vesalius, but he was more extensive and systematic in his dissections and was the first to challenge the teachings of Galen and Aristotle. William Harvey (1578–1657) published his seminal work on the function of the heart and circulation of blood *de motu Cordis et Sanguinis in Animalibus* (1628). Willis (1621–1675) applied this knowledge to his understanding of cerebral anatomy and showed that occluding parts of his eponymous circle did not compromise flow, thereby confirming their anastomotic nature.

Surgery continued to develop in all areas, although neurosurgery remained confined to trauma. In a challenge to orthodoxy, Yonge (1646–1721) stated that mortality was 'not inevitable' once the dura had been breached. Percival Pott not only worked on tuberculosis (TB) of the spine (which has made a recent resurgence in neurosurgical practice) but also made significant advances in our understanding of head injuries. He asserted that in head injury, trepanning could relieve the pressure from extravasated fluid, thus providing a rationale for the oldest neurosurgical operation. At the same time, Jean Louis Petit (1674–1750) described the classic 'lucid interval' associated with an extradural haematoma as a brief loss of consciousness followed by a gradual deterioration due to accumulation of blood compressing the brain. The importance of brain injury rather than head injury began to be recognized. Bell (Edinburgh 1749–1806) described the loss of pupillary reaction to light and recognized this as an indication to perform a 'rapid and prompt evacuation' of an extradural haematoma. Bell is also credited with identifying that hydrocephalus can be associated with spina bifida.

Although the majority of operations were still for trauma, one key exception was the successful extirpation by Morand (1697–1773) of a temporal abscess following otitis media and mastoiditis. He describes exploring it with his finger and washing out the cavity before placing a silver tube which was slowly withdrawn—a method which resonates today, where silver is once again finding a medical role for its bactericidal properties.

Cotugno (1736–1822) further characterized the cerebrospinal fluid (CSF) pathways and described the 'nervous origins' of sciatica for the first time. He also described hydrocephalus *ex vacuo* as being secondary to cerebral atrophy.

The surgeon/anatomist John Hunter (1728–1793) was a student of Pott's and made major contributions to general surgery and neurosurgery. His extensive anatomy collection houses the Irish giant (Cushing's original acromegalic) and can still be seen at the Hunterian Museum at the Royal College of Surgeons, London.

However, during this time neurosurgical operations were still plagued by infection and the lack of anaesthetic agents meant that operations had to be rapid and not always accurate. The clinical skill of cerebral localization was also yet to be described, so surgery was confined to lesions that had external manifestations.

Early modern to nineteenth century

The modern practice of neurosurgery as we know it today began in the nineteenth century. The parallel advances in anaesthesia and antisepsis allowed mortality rates to fall to acceptable levels and the ability to localize cerebral lesions by clinical examination alone allowed surgeons to tackle occult lesions, thereby dramatically broadening the scope of the specialty. These advances ultimately led to the creation of neurosurgery as a specialty in its own right.

Parallel advances

Anaesthesia

The introduction of ether in the 1840s allowed surgery to be performed in a pain-free manner without the surgeon being rushed or restraints being used. The dentist William Morton persuaded Dr Warren to use ether to excise a submaxillary tumour in 1846 at the Massachusetts General Hospital. Shortly after this, in 1847, Marie Jean Pierre Flourens successfully used chloroform anaesthesia. It was not without risk, but the advantages to both surgeons and patients were clear. As anaesthesia became safer, so the range of pathologies that could be tackled grew and complex surgical approaches could be developed.

Antisepsis

Before antisepsis, neurosurgery was almost inevitably fatal due to 'suppuration'. Louis Pasteur (1822–1895) developed his germ theory and radically changed current opinion as to the origins of

infection. He postulated that meat putrefaction and fermentation were not due to 'spontaneous' degeneration but to living microscopic organisms. Joseph Lister (1827–1912), who was Professor of Surgery at the University of Glasgow, applied Pasteur's germ theory to surgery and in particular to wound infections. He began using carbolic acid and commented that his wounds healed without pus. The mortality from amputations was dramatically cut from 45% to 15%. Meanwhile, in America William Keen (1837–1932) adopted Lister's principles in his operating theatre, applying them to the surgeon, the patient, and to the theatre environment; principles that are still being pursued today. He insisted all surfaces were cleaned with carbolic and carpets and furniture were removed. The surgeon's hands were washed with soap, alcohol, and sublimate, and the patients were also prepped for the first time with a head shave, soap and water, ether, and wet sublimate dressings as well as mercuric chloride washings.

Handwashing was also shown to radically reduce infections in obstetrics and gynaecology by Holmes Semmelweiss. Keen boiled his surgical instruments for 2 hours in a precursor to heat sterilization, which was introduced in 1891 by Ernst von Bergman. In 1883 Neuber began to use sterile gowns and caps, but it was not until William Stewart Halsted (1852–1922) commissioned Goodyear to make some rubber gloves in 1890 to protect his nurse's hands from the mercuric chloride that gloves were routinely used in surgery (see Fig. 1.2). Mikulicz subsequently introduced masks in 1897.

Cushing himself stated in 1915 that 'certainly infections cannot be attributed to the intervention of the devil but must be laid at the surgeon's door'. He published his series of 130 cases with only a single infection—an infection rate of less than 1%, which remains enviable today. A Centre for Disease Control and prevention (CDC) audit on craniotomy infection rates from 1992 to 2003 reported rates between 0.86% for low risk cases and 2.32% for the high risk. Cushing also reported a perfectly respectable 8.4% mortality in the same series (Cushing, 1915). In the 1940s antibiotic prophylaxis was introduced to reduce postoperative infection.

Cerebral localization

In the 1860s the correlation of neurological symptoms and signs with the cerebral location of a lesion began to transform the scope of neurosurgery. The neurological examination is so ingrained in our current practice that it is difficult to imagine a time before cerebral localization. At the beginning of the nineteenth century, localization theory had been associated with the discredited pseudo-science of phrenology. Paul Broca (1824–1880) then showed that speech was localized in the brain's left hemisphere and John Hughlings Jackson (1835–1911) described what came to be known as the 'Jacksonian march' of focal motor activity 'in which parts of the body are affected one after another'. He also correctly identified that a third cranial nerve palsy lateralizes the haematoma to the side of the fixed and dilated pupil. He directed Sir Jonathan Hutchinson (1828–1913) to perform surgeries based on his localizations and ipsilateral pupillary dilatation carries the eponym 'Hutchinson's pupil'.

It was during the same period that David Ferrier (1843–1928) was using Faradic current stimulation in animals including primates to create one of the first cortical maps, including the correct location of the motor cortex. He credited Hughlings Jackson with predicting the outcome of his animal studies. Fritz and Hitzig were using similar cortical stimulation techniques to map the cortex in dogs during the same time period.

Dr Alexander Hughes Bennett (1848–1901) is credited with being the first neurologist to direct the removal of a tumour by cerebral localization alone. In 1885 he directed Sir Rickman Godlee (1849–1925) to remove a motor strip tumour from a patient who had presented with contralateral focal motor seizures and subsequent progressive hemiparesis. The operation was successful, but the patient later died of infection, as was so often the case (Bennett and Godlee, 1965; Kerr et al., 2005).

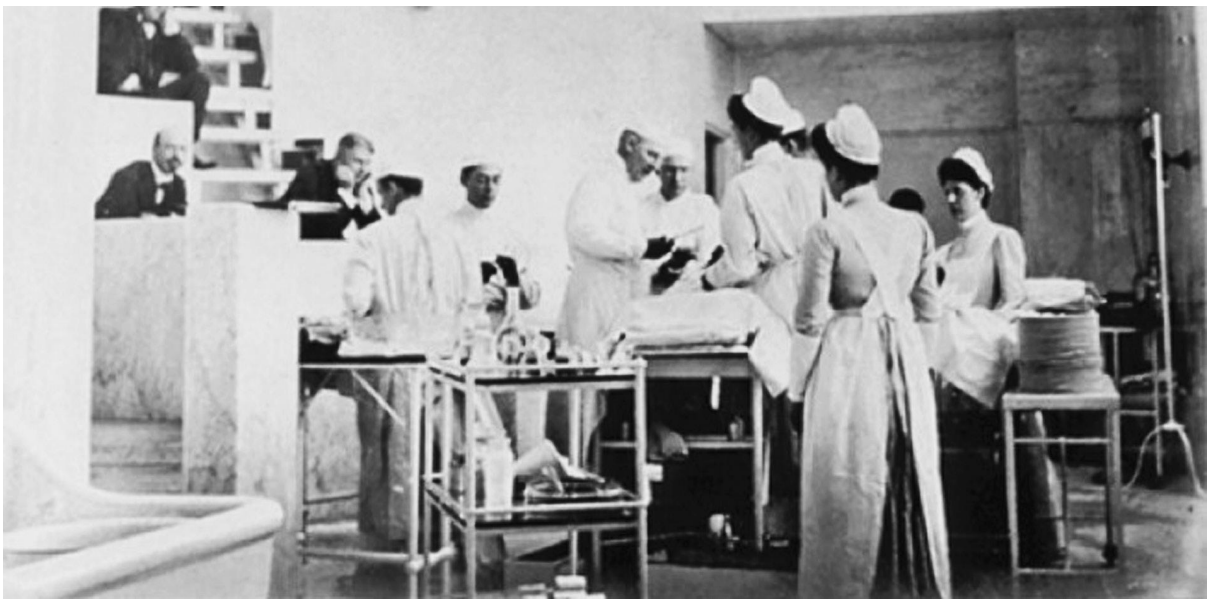

Fig. 1.2 Photograph of Harvey Cushing and William Halsted in the operating room. Note the rubber gloves, made by Goodyear, that Halsted was the first to use routinely in surgery.

Haemostasis

The development of effective neurosurgery required new methods to deal with the torrential haemorrhage often associated with craniotomy. William Bovie (1882–1958) developed the method of electrocautery for haemostasis and it was first used by Cushing in 1926. The development of blood transfusion in the early years of the twentieth century was also of importance. Until then, craniotomies would sometimes be done as staged procedures, with an interval between the operations to allow the patient's own haematopoeisis to replace the blood lost on opening the scalp and skull.

Early pioneers

These major technical advances in anaesthesia, antisepsis, cerebral localization, and haemostasis set the scene for the early pioneers of neurosurgery to establish neurosurgery as a specialty in its own right.

Victor Horsley 1857–1916

Sir Victor Horsley (1857–1916) was a clinician, researcher, and surgeon, and was therefore ideally qualified to make significant advances in cerebral localization. He published works on the topography of the motor cortex and 'the arrangement of the internal capsule', as well as relating surface anatomy to underlying cortical features in 'topographical relations of the cranium and surface of the cerebrum'. In 1888 he was the first to successfully remove a spinal cord tumour (localized by William Gowers, neurologist, 1845–1915). He was not the first to remove a brain tumour—that was William Macewen (1848–1924)—but he is credited with performing several pioneering operations, including craniosynostosis surgery for raised intracranial pressure and sectioning of the posterior root of the trigeminal nerve for neuralgia; he was also the first to operate on the pituitary. His technical advances included the development of antiseptic beeswax for bone bleeding (still used today) and the Horsley-Clark stereotactic frame. He was a general surgeon himself, but was at the forefront of developing neurosurgery as a specialty and was given the first specifically neurosurgical appointment while at Queen Square. He died in the First World War from desert fever.

William Macewen 1848–1924

William Macewen (1848–1924) was born in Port Bannatyne on the Isle of Bute, Scotland. He was Regius Professor of Surgery at Glasgow University from 1892 to 1924 and was knighted in 1909 when he became Surgeon to the King. His major contributions to surgery were in orthopaedics, establishing bone graft surgery, and setting up the Princess Louise Scottish Hospital for Limbless Soldiers and Sailors where he also designed the Erskine artificial limb. He is credited with performing the first brain tumour operation when he successfully removed a presumed meningioma from a 14-year-old girl in 1879. He did not require the then-novel technique of cerebral localization as there was hyperostosis overlying the meningioma, which directed his surgery. She had indeed presented with cosmetic deformity, and subsequently had refractory seizures contralateral to the lesion, which provided Macewen with the indication to attempt the resection. He was a strong believer in sterile surgical techniques and she survived a further 8 years, and was able to work, before dying of other causes. The low mortality of his operations for cerebral abscess bears comparison with modern series.

William W. Keen 1837–1924

The first American neurosurgeon was William Williams Keen Jr. He studied at Jefferson Medical College and was President of the Philadelphia School of Anatomy. As was commonplace at that time he toured Europe during his education, spending time in Paris and Berlin. He is credited with introducing the Gigli saw to America. He pioneered CSF drainage for hydrocephalus, describing the eponymous parietal burr hole still often used for ventriculoperitoneal shunt insertion 3 cm posterior and superior to the pinna. Although not the first to remove a brain tumour, he was noted for removing some large tumours successfully.

Harvey Williams Cushing 1869–1939

Harvey Williams Cushing is often seen as the father of modern neurosurgery (see **Figs. 1.3** and **1.4**). Arriving on the scene at just the right time when antisepsis, anaesthesia, and cerebral localization

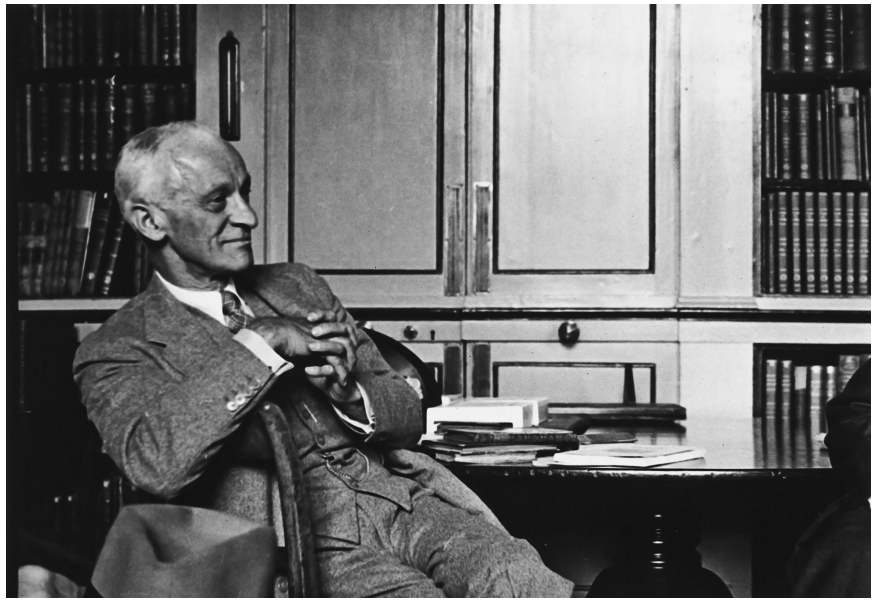

Fig. 1.3 Harvey Cushing, the father of modern neurosurgery.

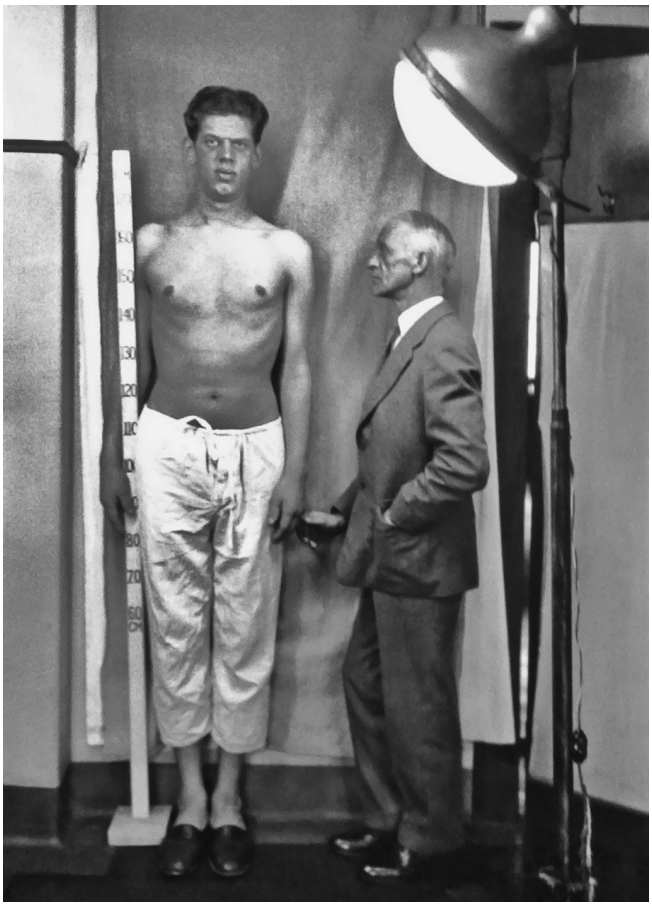

Fig. 1.4 Harvey Cushing stands by a patient with gigantism.
Reproduced from Shin P. Harvey Cushing's Ghosts: Death and Hauntings in Modern Medicine. Yale J Biol Med. 2011;84(2):91–101

were now established, Cushing was well positioned to make his contribution to the specialty.

He was trained in general surgery by Halsted himself, who was Professor of Surgery at the time, and who is credited for teaching Cushing his meticulous surgical technique. Another great influence on Cushing was Sir William Osler (1849–1919), who encouraged him in the more philosophical aspects of medicine including the study of the history of medicine. Cushing was one of Osler's 'latchkeyers', students who lived next door to Osler and were given the 'latchkey' to his extensive library.

In those days it was common for American doctors to spend some time visiting their counterparts in Europe, and Osler encouraged Cushing to do the same. Cushing visited Horsley in London and by his own account was 'a little disappointed' in him. A meticulous surgeon himself, Cushing described Horsley's technique as 'execrable' and commented that he must have many 'septic wounds'. Indeed, at that time Horsley accepted mortality rates of 30–50% from 'brain fungation' (i.e. infection).

Cushing then travelled to France and Switzerland where he worked with Kocher in Bern. In contrast to what he writes about Horsley, he comments that Kocher's technique was 'detailed' and 'tedious' with 'absolute haemostasis'. Cushing's seminal work on intracranial pressure began at this time in the lab of Kronecker. It was here that he made the discovery that 'an increase in intracranial tension occasions a rise of BP which tends to find a level slightly above that exerted against the medulla'—now known as the Cushing reflex. His travels then took him to Italy where he was so impressed with the blood pressure monitor designed by Scipione Riva-Rocci that he brought it back to America with him.

This era from 1901 to 1910 was a key decade for neurosurgery. Cushing recognized the importance of raised intracranial pressure and of meticulous surgical technique. He was responsible for the introduction of intraoperative blood pressure monitoring and following his own experience of a death on the operating table, he also introduced anaesthetic charts to record pulse and respirations during a procedure. With Percival Bailey (1892–1973) and Louise Eisenhardt (1891–1967) he coauthored the standard works on gliomas and meningiomas, and was responsible for pioneering work on the diagnosis and treatment of pituitary disorders.

Walter Dandy 1886–1946

Walter Edward Dandy studied medicine and subsequently spent his whole career at Johns Hopkins Hospital (see **Fig. 1.5**). He was of the same Halsted surgical dynasty as Cushing and was Cushing's research assistant at the Hunterian laboratory that Cushing had established at Johns Hopkins. His work on the production and absorption of CSF acknowledged the importance of the choroid plexus and made advances in our understanding of hydrocephalus of infancy.

His work on 'pneumoventriculography' (1918) radically changed neurosurgery for the next 60 years. In 1913 Luckett had described the radiological appearances of pneumocephalus but Dandy developed the technique by which air ventriculography (or pneumoencephalography as it was known) allowed the interpreter to infer the location of intra-axial masses by the distortion they created in the ventricles. Along with cerebral angiography (discovered by

Fig. 1.5 Walter Dandy, a student of Cushing's and later his rival, made several key contributions to neurosurgery.

Moniz in 1927) this became the mainstay of diagnostic imaging until the advent of the computed tomography (CT) scanner in the 1970s. Previously Cushing and others had used X-rays to identify extra-axial masses such as sellar lesions but until the technique of pneumoencephalography was introduced, intra-axial lesions could only be diagnosed by the clinical skill of cerebral localization. He was the first surgeon to operate for a colloid cyst in 1921.

He advocated total resection of an acoustic neuroma as opposed to Cushing's more conservative subtotal removal, sectioning the fifth cranial nerve for trigeminal neuralgia and developed a transcallosal approach to the pineal. He also identified a ruptured intervertebral disc as a cause of cauda equina syndrome and bilateral sciatica in 1929.

Late twentieth century to today

In recent decades, progress has largely been driven by advances in technology, with the sometimes slightly paradoxical effect of changing management away from neurosurgery, with developments such as interventional radiology for aneurysms and stereotactic radiosurgery for small vestibular schwannomas.

Technological advances

Diagnostic imaging

The development of diagnostic imaging techniques has revolutionized neurological diagnosis (and introduced the modern problem of the incidental finding). Following Dandy's pneumoencephalography the next major advance in imaging techniques was cerebral angiography. This was developed by Antonio Caetano de Egas Moniz (1874–1935) who was subsequently awarded the Nobel Prize in 1949 for the more dubious invention of frontal leucotomy for psychosis (and was also shot and rendered paraplegic by one of his patients). Myelography was introduced by Jean Athanase Sicard (1872–1919) and allowed mass lesions of the spine to be identified.

Parallel advances in X-rays and computing allowed the development of the CT scanner by Godfrey Hounsfield (1919–2004) at EMI. The first CT scan of a patient was in 1971 at the Atkinson Morley Hospital, London, confirming a right frontal lobe tumour. The development of positron emission tomography (PET) and magnetic resonance imaging (MRI) swiftly followed in the 1980s.

Operative microscope

Gunnar Holmgren in Stockholm in 1927 was one of the pioneers of the binocular microscope and its first clinical use was by oto-rhinolaryngologists for the management of otitis media. Several refinements were made to the apparatus, largely led by ears, nose, and throat (ENT) surgeons themselves. Perhaps surprisingly it was not until 1957 that the microscope was first used in neurosurgery. Theodor Kurze, apparently inspired by a film of the ENT surgeon William House using the operative microscope, used it for the removal of a neurilemoma in a 5-year-old.

There are innumerable other advances in the field of neurosurgery. The adoption of the endoscope, for example, has transformed skull base surgery and the introduction of ventriculoperitoneal shunts has radically changed our management of hydrocephalus. These technologies are still, relatively speaking, in their infancy and will continue to develop throughout this century at least.

History of spinal neurosurgery

Although this chapter mainly focuses on the history of cranial neurosurgery, the development of spinal surgery should not be overlooked. Once more, the Edwin Smith Papyrus gives us vivid descriptions of the way spinal trauma was managed in Ancient Egypt. The ability of the Ancient Egyptians, and in particular Imhotep (thought to be the world's first physician) to tie in the clinical picture with the management plan and the prognosis was remarkable. Case 31 clearly describes a complete spinal cord injury secondary to a cervical vertebra dislocation—centuries before Brown-Séquard's treatise on spinal localisation in 1858.

The Hippocratic School in Ancient Greece described the first traction device, advocating correction of an acquired kyphosis following trauma. Hippocrates recognized compression of 'spinal marrow' by displaced vertebrae as the cause of paralysis. As in Ancient Egypt, no treatment was advised if the patient was paralysed. Celsus and Galen did not advocate surgery either, recognizing the poor outcomes associated with spinal cord damage, especially once urinary dysfunction had occurred. Celsus recognized that high cervical lesions were associated with quadriparesis and respiratory compromise while thoracic lesions led to paraparesis. Galen (131–201 AD) coined the terms kyphosis, lordosis, and scoliosis. It is worth noting that he also was the first to describe tuberculous spinal disease (a few hundred years before Percival Pott 1713–1788) and, having conducted experiments where he demonstrated that spinal cord transection led to loss of function below the level of the lesion, he also contributed to the conceptual advance of the brain as the source of voluntary action with signals being passed along the spinal cord. Paulus of Aegina (624–690 AD) was the first to advocate surgery on the spine, removing bony fragments in injured patients with paralysis. Interestingly, in an early reference to 'informed consent' he describes his surgery as being carried out 'after warning of the dangers'.

Very little progress was made in the mediaeval period and the 'dark ages' in Europe. The seat of medicine was transferred to the Arabic world. Previously acquired knowledge from the Alexandrian and Hippocratic schools was preserved by translating the Latin documents into Arabic, but not advanced in any significant way. One notable exception is the Turkish physician Sabunuoglu (*b.*1385) who provides us with the first description of treating sciatica—the first description of degenerative rather than traumatic spinal disease. It was not until 1764 that Cotugno postulated that neural compression was the source of sciatica, a model that was later added to by the French neurologists Lasegue, Dejerine, and Sicard.

During the eighteenth and nineteenth centuries, the Age of Enlightenment in Europe, the foundations for modern spinal surgery were built. Percival Pott (1713–1788) described his now eponymous tuberculous spinal disease and washed out a paravertebral abscess with some success. John Bell (1763–1826) described the flaccid and spastic paralysis and sphincter disturbance associated with spinal cord injury and, with regards to spinal surgery, is quoted as saying 'the cutting into a vertebra is a dream' in 1799. Mr Cline Jr, a surgeon at St Thomas' Hospital, London, is credited with the first 'trepanation' of the spine in 1814 on a paralysed man who was paraplegic after falling from a balcony. He performed a laminectomy and removed the facet joints to reduce the dislocation, but the patient died. There are reports from military history of surgeon Louis operating

on Captain Villedon, who had sustained a spinal cord injury from a thoracic gunshot wound and reportedly regained some distal function postoperatively.

Surgery remained controversial due to its high mortality and morbidity until the advent of antisepsis (Lister 1882–1912 and Semmelweiss 1818–1865) and safe general anaesthesia. Spinal cord localization mirrored cerebral localization with the early work being carried out by Blesius in 1666 (he described the grey-white matter differentiation) and the anterior-posterior spinal nerve roots. The decussation of the pyramids was described by Mistichelli in 1709 and Huber described the denticulate ligaments in 1739. The substantia gelatinosa was described by Rolando in 1809 and Brown-Séquard's description of the decussation of the sensory tracts was published in 1846. Brown-Séquard was a strong advocate of surgery for spinal cord injury. His contribution to spinal cord localization and his description of the spinal cord tracts is immortalized in his eponymous syndrome of hemisection of the cord. Further work on biomechanics of the spine was carried out *in vivo* and *in vitro* by Rauber, Weber, and Messerer in the 1800s.

In the late 1800s, spinal surgery was still mostly confined to trauma and infection (TB). Almost two centuries after Cotugno described the neural compression in sciatica, Oppenheim and Kruse described the first surgery for disc herniation (1909). Mixter and Barr fully described the pathogenesis of disc herniation in 1933 and advocated a 'transdural' approach to the disc. In 1977 Caspar and Yasargil described the microsurgical intralaminar extradural approach that is practised today. Critical to these developments had been Roentgen's discovery of X-rays in 1895, radically improving the diagnosis of spinal fractures. Previously spinal fractures were thought to be almost invariably associated with neurological deficit (90%). Sudeck developed the systematic interpretation of X-rays and established that most fractures in intact patients were missed and that therefore the true rate of paralysis was more like 15–20%. The advent of imaging modalities such as CT (1970s) and MR (1980s) had an equally great impact on the development of surgery for degenerative spinal disease.

Although a few key spinal operative 'firsts' are attributed to nineteenth-century surgeons, it has been the twentieth century where advances in imaging and materials science has allowed the field of spinal surgery to expand into spinal fixation. Anterior, posterior, and lateral approaches to all regions of the spine were developed. The cervical spine has particular challenges due to its poor biomechanical strength and the proximity of important neural and vascular structures. During the last 50–100 years, we have seen the progression from the first anterior cervical surgery of Bailey and Badgley in the 1950s who described the anterior cervical discectomy (ACD) without any graft, to the ACD and fusion (ACDF) advocated by Cloward in 1958 and then by Smith and Robinson. The first anterior cervical plate was designed by Orozco and Lovet and required bicortical screws, which are technically challenging to place. Technological and biomechanical advances allowed the introduction of the unicortical locking screw and then the dynamic load-sharing plates with variable angle screws which was introduced in 2000. Throughout this time, posterior approaches to the subaxial spine have also benefited from advances in materials science with stronger, lower profile screws and posterior cervical fixation has moved forward from the silver wire used in the first posterior c-spine fixation in 1891 via interspinous wires (1942 by Rogers), sublaminar wires (1970), facet wires, and eventually Roy-Camille's lateral mass screws in the 1980s. The history of spinal fixation warrants a chapter in itself. Key advances took forward the principles of open reduction and internal fixation used by orthopaedic surgeons for long bone fractures and applied them to the spine. In 1953 Holdsworth and Hardy described a system of plates and screws. Transpedicular screw fixation was described by King in 1944 but not implemented until 1959 by Boucher. In 1958 Harrington described his system of dorsal instrumentation to correct scoliosis—initially due to polio and then applied to idiopathic. Ventral scoliosis surgery was first described in 1964 by Dwyer. The early focus in disc surgery was to preserve motion and avoid stiffness; this was challenged subsequently when the pathology of disc herniation was found to be secondary to instability and the drive towards fusion became popular. Contrary to this belief, others have focused on developing motion-preserving disc replacements first proposed by Fernstrom in 1966 and patented (although never implanted) by Froning in 1975. The charité intervertebral disc is now the most commonly used artificial disc.

Intradural spinal tumour surgery has progressed along similar lines to cranial surgery, with the first successful removal of an intradural tumour being credited to Horsley in 1887. Elsberg performed the first successful removal of an intramedullary tumour in 1907 and described a two-stage technique for myelotomy and then tumour removal at a second sitting. The technique of pneumoencephalography developed by Dandy was also useful in the spine and, of course, the introduction of the operating microscope greatly improved the success of intradural and intramedullary resections.

Technological advances continue at a rapid pace in spinal surgery. Recent advances in minimal access surgery, image guided screw placement, and endoscopic approaches have all developed in the last 30 years. The thoracoscopic discectomy and fusion of the 1990s has progressed to the treatment of scoliosis and corpectomies using minimal access. Laparoscopic discectomies also developed at a similar time. The father of endoscopy Desormenaux in 1853 could not have foreseen its current myriad applications. Spinal surgery continues to be a rapidly expanding field and the current population demographics mean there will be no shortage of demand for the treatment of spinal trauma, infection or, of course, the degenerative spine.

The future of neurosurgery

The last 100 years have brought dramatic advances in the practice of neurosurgery. The future is likely to see a further move away from open cranial surgery to minimally invasive, endoscopic, and radiologically guided interventional techniques.

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2

Clinical assessment

Peter Bodkin and Elizabeth Visser

Introduction

The practical process of clinical assessment in modern neurosurgery is slightly different to the traditional model. The ground rules of history taking and examination set down by William Osler and the other forefathers of clinical method rightly remain core to our approach, but we must also take into account the realities of the patient journey before the first encounter with a neurosurgeon. Whether by the bedside or in the outpatient setting, it would be rare nowadays for us not to have already been presented with pertinent background information—and indeed, often we will have seen high-quality imaging detailing the patient's pathology with great anatomical detail. The referring physician will most likely have provided a potential list of differential diagnoses. In other words, the patient has usually been neatly packaged well before we ever get to meet them.

Our job, however, is more than simply to supply a surgical fix to a given problem. We are not merely technicians. Although we must take into account the information given to us, we must never take it on face value. All sorts of errors in assessment and incorrect conclusions may have been made along the way. Likewise, imaging is very useful but should never be viewed outside the clinical context. An MRI scan will localize a lesion with more confidence than the best clinician, but technology cannot make us consider a diagnosis of acromegaly from a spongy handshake or common peroneal palsy from the sound of a slapping foot coming to the clinic door.

As we gather and make sense of this information there is an equally, if not more, important process at work. By putting the patient's symptoms into the context of their daily life we begin to develop a relationship with the patient, starting to establish trust and mutual understanding. The rapport built here will be the basis of how a patient measures the success or failure of our interventions.

The traditional neurological clinical assessment described in most textbooks has other subtle differences to those required of the neurosurgeon. This chapter aims to cover that broad spectrum of clinical method for the practising neurosurgeon and those in training.

The neurosurgical history

The main aim of the neurosurgical history is to gain sufficient information to estimate the anatomical location of the problem and to get an impression of the pathological process at work. In particular, the time course and severity of the symptoms will be important guides as to whether surgical intervention is required and how quickly.

As with any important task, being well prepared will provide a good first impression and will save time in the long run. Referral letters, clinical notes, imaging, and other investigations should have been carefully reviewed. Prior discussions with relevant team members may also be useful.

In the clinic, calling the patient from the waiting room yourself can be very valuable. An impression of their social support may be gained by seeing who is with the patient and how attentive they are. Anaesthetic fitness can be crudely assessed by how long it takes to get up and into the clinic room or how out of breath they might be. It is also an opportune moment to make an assessment of gait and a note of walking aids, and so on.

Thought should be given to the physical environment for the meeting. This should be arranged such that the patient and doctor are on as level a playing field as possible. One should be aware that being at a higher eye level or sitting behind a desk may have an intimidating effect and will detract from getting the most out of the encounter. When dealing with digital images, viewing platforms should already be opened with relevant images downloaded.

Introductions should be clear, giving your name and position. Significant others should be welcomed and acknowledged but it should be made clear that the patient is the focus of discussions.

How you open the consultation is important. One should start with open questions, 'So what's been the trouble?', or 'How can I help you?' The referral letter or consultation request has a tendency to emphasize the symptoms that will lure you into seeing the patient in the first place. It is wise, therefore, to avoid saying things like, 'So your doctor has asked me to see you about your facial pain?' Assumptions can be misleading and may encourage patients to tell you what you are expecting to hear.

Once you have encouraged the patient to tell their story, it may be necessary to fill in some gaps. The patient may have painted a picture but there could be large areas missing or fundamental details that are only sketchy. When it comes to the information that is going to influence your decision on treatment keep delving until you feel there is satisfactory detail for a conclusion to be drawn. In the course of this it is important to remember to find out the occupation of the patient and often handedness is pertinent. It is not enough to say a patient

is 'retired'. A retired university professor will have quite different expectations in life compared to a retired ship builder.

The history taking needs to cover time course, anatomical location of symptoms, variability, and character. One must refine questioning with the aim of localizing the lesion or getting clues as to the underlying pathological process. If a patient is not volunteering a symptom, one must consider symptoms that might be associated and ask about them directly. For example, when assessing a patient presenting with spatial disorientation due to a right parietal tumour one needs to remember to ask about problems with their visual fields in case of involvement of the optic radiation, and so on.

The most vital part of the story is often the impact that the condition is having on the patient's way of life. It may seem an unnecessary intrusion to pursue this but most patients are happy to let you know their problems and the knock-on effects on their home, work, and family life. By establishing that you are not solely interested in dealing with their particular pathological entity but rather you want to help them get back to doing the things they enjoy, you turn a medical interview into a more meaningful conversation. The patient will understand that you are treating them and not just their tumour or slipped disc.

Pick up cues. Have an ear for the incongruous. If what you hear doesn't make sense, explore it. Don't let it pass unmentioned. It is also useful to find out what has been done so far to address the problem: pain killers, physio, injections, visits to other physicians, and so on. Is the patient fit for an anaesthetic? Are there drugs that need to be stopped prior to surgery? Could an unhealthy lifestyle be contributing to the problem?

Drawing the history to a conclusion, the patient should feel that their issues have been adequately addressed. 'Is there anything else you'd like to discuss?' is a useful way of allowing any additional information to be voiced. The patient will hopefully be in a more relaxed and open frame of mind by this stage of the interview and might reveal underlying motivations and concerns. Finally, it may be useful to agree on a brief summary and have a final effort to clarify any lingering grey areas or inconsistencies.

The neurosurgical examination

Examination of the unconscious patient

The approach to the patient who has altered conscious level is obviously limited by the inability of the patient to comply with given instructions and to provide verbal feedback. We are therefore restricted to rather crude and basic bedside tests (i.e. examination of pupillary response to light and the Glasgow Coma Score). Often high-stake decisions are made on the basis of these assessments and it is therefore crucial that they are performed with utmost care, being mindful of possible confounding factors (Table 2.1).

Impairments of pupillary response may be due to damage at a number of locations along the afferent and efferent pathways. Direct trauma to the orbit may cause rupture of the pupil sphincter muscles and produce a traumatic mydriasis. Traumatic optic neuropathy may be due to direct disruption due to penetrating injury or indirectly by shearing forces in blunt head trauma. Lesions in the region of the pretectal nuclei or Edinger–Westphal nuclei in the rostral midbrain will also cause mydriasis. There are complex regulatory pathways from various sources including the ipsilateral hypothalamus that drives sympathetic pupillary tone and indeed poorly understood descending control from the cortex that results in ipsilateral or contralateral mydriasis or miosis following a seizure (Plum and Posner, 2007). Therefore, damage in many brain regions may result in pupillary abnormalities (Fig. 2.1). Compression of the parasympathetic fibres along the third cranial nerve by the herniating uncus is a common cause of pupillary abnormality in neurosurgical practice.

Table 2.1 Confounding factors in assessment of GCS

Glasgow Coma Score	Confounding factors
Eye opening (4 = spontaneous, 3 = to speech, 2 = to pain, 1 = do not open)	Orbital injuries Ecchymosis Photophobia
Verbal response (5 = oriented, 4 = confused, 3 = inappropriate words, 2 = incomprehensible sounds, 1 = no sound)	Non-native speakers Maxillofacial injury Endotracheal intubation/tracheostomy Deafness
Motor response (6 = obeys commands, 5 = localizes to pain, 4 = flexion/withdrawal to pain, 3 = abnormal flexion to pain, 2 = extension to pain, 1 = no movement)	Spinal cord injury Upper limb fractures, casts, and fixation

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The Glasgow Coma Score brings together diverse clinical features to provide a guide to global brain function. Of the three divisions (eye opening, verbal response, and motor response) the motor response is most likely to differentiate the severity of injury. Lesions above the red nucleus produce decorticate posturing (flexion of upper limbs and extension of lower, rubrospinal tract function) and those below produce decerebrate posturing (extension in upper and lower limbs, vestibulospinal tract function). Normal flexion (M4) constitutes flexion with supination; abnormal flexion (M3) constitutes flexion with pronation analogous to decorticate posturing and release of rubrospinal tract function as just described; and extension (M2) is analogous to decerebrate posturing and release of vestibulospinal tract function. It is best to apply painful stimuli to trigeminal territories in case of spinal cord injury causing peripheral numbness. Pressure over the supraorbital notch is sufficient.

Rising blood pressure, falling heart rate, and altered respiratory pattern (Cushing's triad) is a classical response to raised intracranial pressure but is usually a very late, agonal feature.

Examination of language and speech disorders

It is important to appreciate any abnormalities of speech and language as this can impact on the history taking, neurological examination, and assessment of higher function and thus alter the outcome of the consultation in general. The ability to correctly identify disorders of speech can aid in localization of neurological pathology. In order for us to communicate through speech and language, hearing, understanding, voice production, articulation, consciousness, thought, and word finding must be intact. Language is a complex

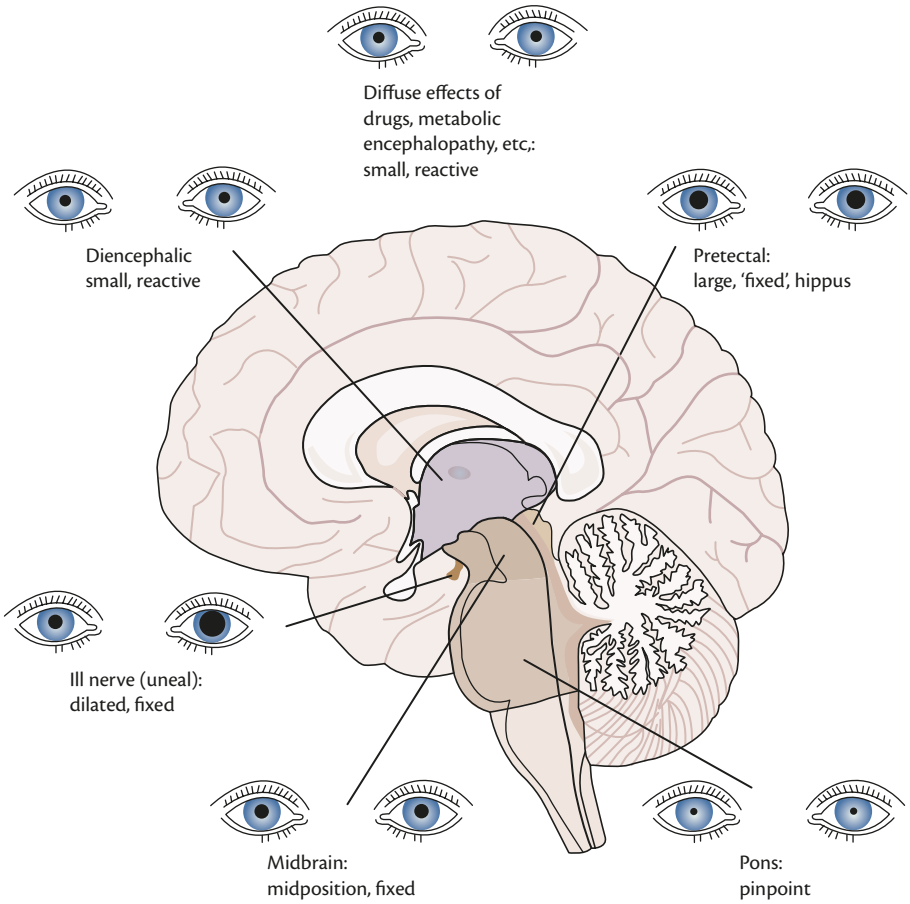

Fig. 2.1 Typical pupillary abnormalities associated with anatomical location of damage.
Reproduced with permission from Kandel et al., *Principles of Neural Science*, Fifth Edition, McGraw Hill, New York, Copyright © 2000.

interaction of combinations of sounds, writing, and meaning often linked to a cultural background.

To assess understanding start by engaging the patient in normal conversation and asking simple questions: 'What is your name? What is or was your occupation? How did you get here today?' Ensure that the patient can hear you properly and enquire as to what their first language is. Establish if the patient is left- or right-handed. As a rule of thumb, 99% of right-handed individuals have language dominance in their left hemisphere; 60% of left-handed patients will be left hemisphere dominant; 20% bilateral; and 20% right hemisphere dominant.

Now consider the different disorders of language defined here:

1. Aphasia—this is defined as a disorder of spoken language. It is divided into subcategories as follows:
   - **1.1** Non-fluent aphasia (anterior, motor, or Broca's);
   - **1.2** Fluent aphasia (posterior, sensory, or Wernicke's);
   - **1.3** Conduction aphasia;
   - **1.4** Transcortical aphasia (sensory and motor).
2. Alexia or dyslexia is a disorder of acquired reading ability.
3. Agraphia or dysgraphia is defined as disorders of written language.
4. Dysarthria is a disorder of articulation or speech production.
5. Dysphonia is defined as an abnormality of noise production by expired air over vibrating vocal cords.

Further examinations of these disorders include assessment of spontaneous speech, fluency, naming, repetition, articulation, speech volume, reading, and writing, and will help to localize the pathology.

1. Assessment for aphasia

Assess spontaneous speech, fluency, and if the patient uses the wrong words (paraphasia). Ask the patient to name animals or words beginning with 'F' in a minute. This tests word finding ability. Also ask them to name familiar objects: a pen, a watch, a tie, and so on. Now ask the patient to repeat phrases. Table 2.2 summarize the findings on examination and localization.

2. To assess for alexia or dyslexia, ask the patient to read a sentence or obey a written command.
3. Agraphia or dysgraphia can be examined by asking the patient to write a sentence; this can only be assessed if there is no motor disability.
4. Dysarthria is examined by asking the patient to repeat a phrase; for example, 'red lorry, yellow lorry' requires intact lingual function and 'baby hippopotamus' requires intact labial function. Listen for slurring and rhythm of speech. Dysarthria can be described as spastic (caused by pseudobulbar palsy as in motor neuron disease), extrapyramidal (associated with Parkinsonian syndromes, often associated with dysphonia), cerebellar dysarthria (associated

Table 2.2 Assessment of aphasia (Clark, 2009; Fuller, 2013)

	Comprehension	Fluency	Naming	Repetition	Other features	Localization
Non-fluent aphasia	Intact	Non-fluent	Impaired	Impaired	Right hemiplegia, depressed	Left frontal lobe (inferior and temporal insula), Broca's area
Fluent aphasia	Impaired	Fluent	Can be intact	Impaired	Neologisms, meaningless speech, paranoid, could have a visual field defect	Posterior superior temporal lobe, Wernicke's area
Conduction aphasia	Intact	Fluent	Impaired	Impaired	Depressed, cortical sensory loss right arm	Parietal operculum/ arcuate fasciculus
Global aphasia	Impaired	Non-fluent	Impaired	Impaired	Right hemiparesis worst in arm	Peri-Sylvian, both Wernicke's and Broca's areas
Nominal aphasia		Non-fluent	Impaired			Angular gyrus
Transcortical motor aphasia	Intact	Fluent	Impaired	Intact	Halting, effortful speech	Left anterior superior frontal area
Transcortical sensory aphasia	Impaired	Fluent	Can be intact	Intact	Semantic paraphasia	Posterior temporo-occipital-parietal area
Transcortical mixed aphasia	Impaired	Non-fluent	Impaired	Intact		Both Wernicke's and Broca's areas

Data from Clarke, C; Howard, R; Rossor, M; Shorvon, S. (2009) *Neurology: A Queen Square Textbook*. Wiley-Blackwell (p. 252–4), Fuller, G. (2004) Neurological Examination Made Easy, 3e. Churchill Livingstone. (p. 17–25).

with multiple sclerosis, alcohol intoxication, or inherited ataxia), and lower motor neuron dysarthria (this is caused by lesions affecting palatal movement causing nasal speech, tongue movements causing patients to struggle with the letters 'T' and 'S' and facial movement resulting in difficulty with the letters 'B', 'P', 'M', and 'W' and often involves the lower cranial nerves).

5. Finally listen to the volume of speech; if this is reduced it is described a dysphonic speech.

The lobar examination

The examination of the functions of the individual lobes of the brain should be a familiar and fluent part of the neurosurgeon's assessment. One should be aware of the somewhat arbitrary divisions between the lobes, however, and it may well be that one should test more than one lobe if the lesion is on or near a dividing sulcus. Anatomically, Yasargil's seven lobe system is most satisfactory (frontal, central, parietal, occipital, temporal, insular, and limbic; see Ribas, 2010) but here we will use frontal, parietal, temporal, occipital, and cerebellum.

Frontal lobe

As one might expect, as it is the largest lobe, frontal examination has the most components and complexity (Box 2.1). Anatomically, it is useful to consider four distinct regions—the precentral gyrus, the dorsolateral cortex, the orbitofrontal cortex, and medial cortex (Fig. 2.2).

The assessment of the function of the primary motor cortex requires testing for upper motor neurone signs on the opposite side. The patient may adopt postures typical of pyramidal weakness (i.e. flexors stronger than extensors in the upper limbs and vice versa in the lower limbs). Pronator drift is perhaps the archetypal neurosurgical test and is extremely useful in bringing out subtle weakness. Lying anterior to the primary motor cortex lies an area known laterally as the premotor cortex and medially as the supplementary motor area (SMA). The functions of these areas are complex but act in conjunction with the primary motor cortex. The cortical area immediately anterior to the primary motor cortex (Brodmann's Area 6) comprises of the lateral premotor area on the lateral aspect and the SMA on the medial and interhemispheric aspect. The lateral premotor area has reciprocal connections with the cerebellum and is involved with refinement of movements with external sensory cues. The SMA has reciprocal connections with the basal ganglia and is involved with initiation of movements from internal sensory cues. In contrast to the primary motor cortex homunculus (leg medial, upper limb, face, and tongue lateral) the SMA homunculus is arranged horizontally (leg posterior adjacent to the paracentral lobule and primary motor area for leg, upper limb, then face and tongue more anteriorly). The SMA has roles in postural stability in walking, initiating and sequencing movements, and coordination of both sides of the body. Frontal lobe ataxia causes a characteristic magnetic gait as if stuck to the floor (Brun's apraxia). This has similarities to Parkinsonian gait, but does not have the lack of arm swing. It is part of the clinical triad of normal pressure hydrocephalus (disturbance of gait, continence, and cognition). This reflects the anatomical proximity of the micturition inhibitory area (just inferior to

Box 2.1 Scheme for frontal lobe assessment

- Ask about handedness and assess speech
- Observe behaviour—abulia, inappropriate dress, verbal dysdecorum
- Posture/gait—decorticate, 'magnetic'
- Pyramidal weakness
- Saccadic eye movements
- Primitive reflexes
- Look for urinary catheter
- Anosmia and Foster Kennedy syndrome
- Neuropsychological tests—echopraxia, perseveration, conceptualization, working memory

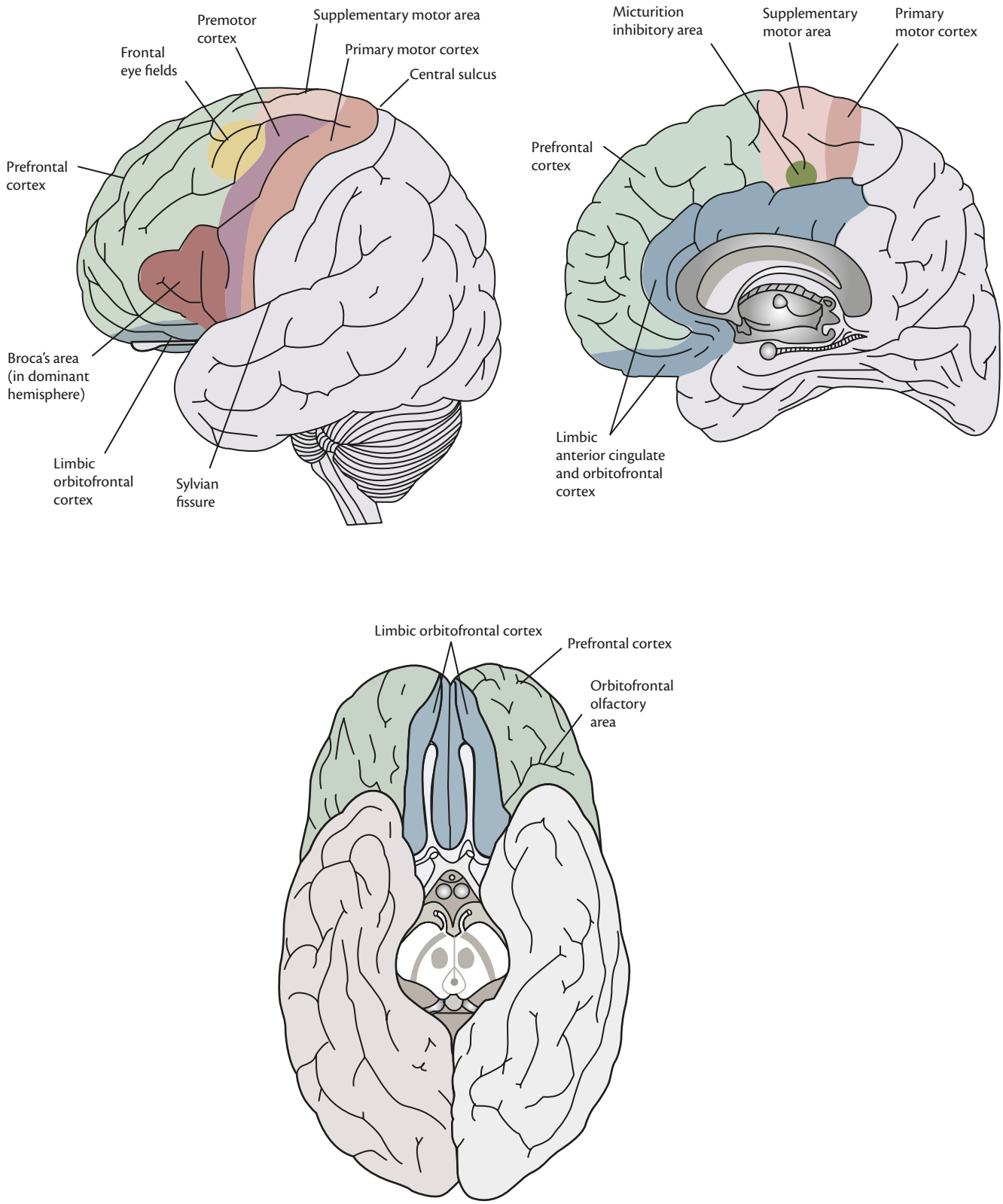

Fig. 2.2 The frontal lobe.
Neuroanatomy through Clinical Cases, 1st Edition by Blumenfeld (2002) Fig.19.11 p. 848. By permission of Oxford University Press, USA.

the SMA) and the more diffuse role of the frontal lobe in cognition. Frontal lobe dysfunction may also cause gegenhalten—the resistance to passive movement.

The frontal eye fields (FEFs, Brodmann's Area 8) lie in the posterior part of the middle frontal gyrus and adjacent precentral sulcus. A mass lesion here may result in horizontal conjugate gaze deviation

towards the side of the lesion (Prévost or Vulpian sign). Seizures will result in looking away from the lesion. Saccadic eye movement should be tested by asking the patient to look between two fixed points (e.g. a fist and a finger) while keeping the head still. Damage to the FEF may result in impaired saccades away from the lesion.

Re-emergence of primitive reflexes or 'frontal release signs' may also be demonstrated. The grasp reflex is assessed by gently passing a finger across the palm. It is most reliably done by distracting the patient by asking them to count backwards from ten. The palmomental reflex is a brief contraction of the ipsilateral mentalis muscle in response to stroking the palm. The snouting reflex is seen when the lips purse in response to tapping the upper lip or the sucking reflex when pressing an object to the lips. Glabellar tap may also cause persistent blinking, whereas in the normal individual it attenuates. It should be remembered that these reflexes may well be seen in normal individuals, particularly in older people (25% of normal adults have the palmomental reflex; see Brazis et al., 2011).

The prefrontal area contains a large volume of brain that has complex roles in control of behaviour. One may divide these into restraint (the restriction of behaviour to that which is socially and culturally acceptable), initiative (motivation to put thoughts into action), and order (to sequence tasks appropriately; see Blumenfeld, 2002). Simply observing and talking with the patient will give insights into this. Apparently quite contradictory behaviours may be encountered, some patients lacking any kind of 'get up and go' compared to others for whom it is difficult to stop talking, or who are overfamiliar or tactless. In general, abulia is more frequently seen in lesions of the dorsolateral convexity whereas disinhibition is often an orbitofrontal feature. There are many neuropsychological tests that are pertinent to examining the frontal lobes (**Box 2.2**).

Parietal lobe

The parietal lobe (**Fig. 2.3**) may be divided into the postcentral gyrus, posteriorly is the superior parietal lobule and inferior parietal lobule (angular and supramarginal gyrus). Processing of somatic sensations and perceptions occurs in the postcentral gyrus (monomodal); the posterior parts are polymodal assimilating inputs from somatic, visual, and other sensory modalities mostly for the control of movement especially the hand and upper limb (Kolb and Whishaw, 2009). The left inferior parietal lobule has a role in language and is considered under that heading. Disorders of the parietal lobe will impair sensation. However, as much of somatic sensation is processed in the thalamus there will not be complete numbness but rather more subtle impairments. These may be tested looking for sensory extinction, astereoagnosia, dysgraphasthesia, and two-point discrimination (**Box 2.3**).

Lesions of the dominant parietal lobe have been associated with a collection of signs known as Gerstmann's syndrome. Although rare in combination, it is still useful to have these four signs in mind for completeness of examination (**Box 2.4**). For the non-dominant parietal lobe (**Box 2.5**) there is a preponderance for there to be contralateral neglect. This may be noted from the patient's appearance with lack of grooming on one side. Other features may become apparent such as loss of geographical orientation (getting lost in familiar places), dressing apraxia, and anosognosia (lack of awareness of illness).

Box 2.2 Neuropsychological tests of frontal lobe function

Luria's three-step test
This tests motor sequencing. Tell the patient you are going to show him a series of hand movements. Without verbal prompting show a sequence of fist, edge, palm, and repeat five times. Ask the patient to do the same. The patient may demonstrate perseveration with repetition of the same movement or be quite unable to do the sequence in order.

Go/no-go test
This tests ability to shift set. Hold two fingers out palm down—'put out one finger when I do this', hold down one finger—'put out two fingers when I do this'. Do this several times. Then change the instructions. Place two fingers—'put out one finger when I do this'. Place one finger—'do nothing when I do this'. The inability to follow the second set of instructions implies a deficit.

Verbal fluency
Produce as many words beginning with a particular letter in one minute, proper nouns not allowed. Normally 12 or more.

Tower of Hanoi
A game moving discs between stacks aiming to achieve goal in as few moves as possible

Wisconsin card sorting test
This is a card matching test testing executive function.

Stroop test
Read out a list of coloured words (i.e. the word green spelt out in yellow text). Test of restraint.

Temporal lobe

The temporal lobes have roles in processing auditory information (Heschl's gyrus), visual information (inferotemporal cortex), emotion (amygdala), and memory and spatial navigation (hippocampus). Its role in language is important especially in the vocalization (dominant) and perception of (non-dominant) emotion in language (emotional prosody). It should be recalled that Meyer's loop passes over the roof of the temporal horn and lesions may, therefore, cause a 'pie in the sky' quadrantanopia. Apart from simple tests of memory, speech, and visual fields there are limited bedside tests for the temporal lobe. Neuropsychologists may perform dichotic listening tests where different recordings are presented to either ear of a pair of headphones to assess selective auditory attention or may carry out advanced tests of verbal and non-verbal memory.

Occipital lobe

Vision and its interpretation is the primary function of the occipital lobe and is dealt with in that section.

Cerebellum

The cerebellum coordinates smooth, planned motor actions by analysing extensive sensory inputs from the brain and spinal cord. The midline structures (the vermis and flocculonodular lobes) control coordination of trunk and eye movement. The cerebellar hemispheres maintain control of limb movement and aid motor planning. Because cerebellar outputs remain ipsilateral or cross twice, lesions of a cerebellar hemisphere will cause an ipsilateral deficit. Ataxia is a characteristic sign of cerebellar dysfunction. Movements are clumsy due to poor coordination between agonist and antagonist muscle groups. There is imprecision of trajectory though space (dysmetria) and also in timing of movements. Truncal ataxia may make even sitting up in bed very difficult. Gait may be wide-based and staggering. Appendicular ataxia may be tested by asking the patient to repeat rapid alternating movements of the limbs (e.g. supinating/pronating one hand on the other). When abnormal this is known as dysdiadochokinesia. One can also ask the patient to outstretch their arm, then touch their nose, or to touch the examiner's finger and back to their nose. An intention tremor may be also elicited. Holmes

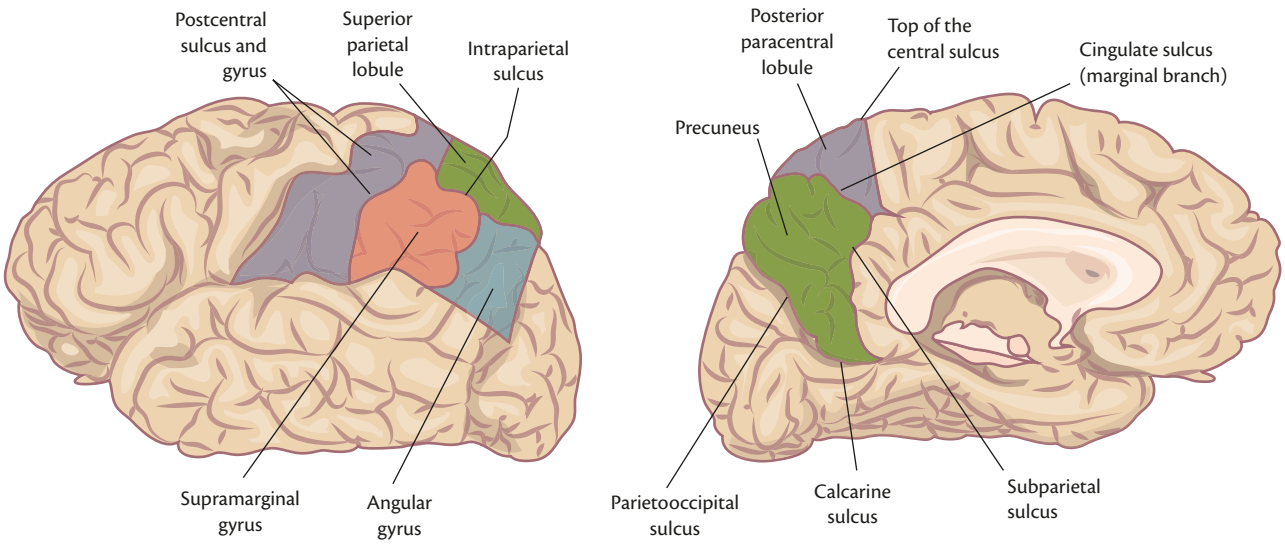

Fig. 2.3 Parietal lobe.

rebound test demonstrates overshooting. For example, with arms outstretched and eyes closed, the examiner pushes one arm downward. On release the patient's arm shoots up higher than originally placed. There is ipsilateral hypotonia and a pendular knee jerk may be found. The cerebellum has a role in articulation and when damaged will cause dysarthria with laboured, slurred speech. Mutism is a well-recognized problem following surgical resections in the midline, well documented in children following medulloblastoma resection. The anatomical basis is from disruption of a dentato-rubro-thalamo-cortical pathway such that bilateral dentate nucleus injury causes mutism. This explains why dominant hemisphere SMA injury, bilateral thalamotomies and mesencephalic strokes (red nucleus) can result in the same syndrome. Cerebellar mutism was originally, mistakenly, attributed to approaches that split the vermis given the close proximity of the dentate nuclei to the midline.

Nystagmus may also be present with the fast phase towards the abnormal side. Vertical nystagmus (e.g. downbeat nystagmus may be seen in Chiari malformation). Head tilt may occur in children with posterior fossa lesions. Cognitive-affective symptoms are increasingly being recognized in cerebellar disorders.

Box 2.3 Examination of parietal lobe function (either hemisphere)

Sensory extinction
Ask patient to hold out arms with eyes shut. Touch either one or both sides of the corresponding part of the body and ask where he has been touched. Extinction occurs when the patient says that only one side is being touched when in fact it is both.

Stereognosis
With the patient's eyes closed, place a familiar object in their hand and ask them to identify it. Coins of different denominations may be used.

Graphesthesia
Ask the patient to identify the number or letter that you trace on their palm. It should be agreed which way is up before starting.

Two-point discrimination
Using callipers or a bent paper clip, ask the patient if they can feel one or two points. On the fingertips one should be able to recognize two separate points to about 2–4 mm apart, on the palm 8–15 mm.

Visual fields
Examine for homonymous inferior quadrantanopia.

Constructional apraxia
Ask patient to copy a 3D drawing.

Box 2.4 Parietal lobe examination—dominant hemisphere (Gerstmann's syndrome)

Dyscalculia
Ask the patient to subtract 7 from 100 and continue subtracting 7 sequentially.

Agraphia
Ask the patient to write a simple sentence.

Finger anomia and left-right disorientation
These two can be examined together by crossing your hands and asking, 'Which finger am I wiggling?' (Fig. 2.4) or alternatively asking the patient to touch their right ear with their left ring finger. Remember to also assess speech (see earlier).

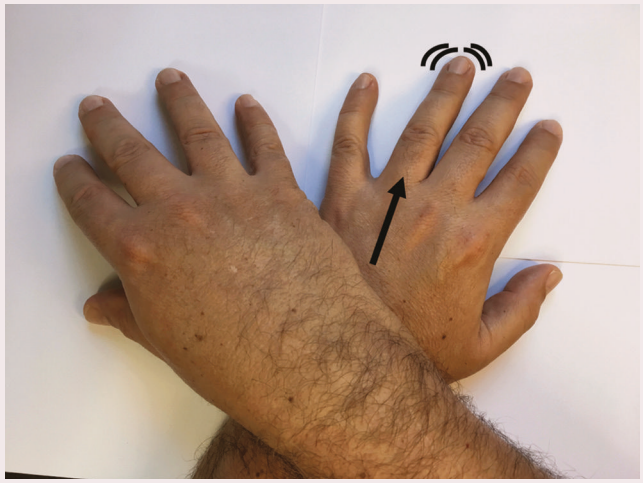

Fig. 2.4 Testing finger anomia and left-right disorientation: 'Which finger am I wiggling?' Correct answer: 'Your left ring finger.'

Box 2.5 Parietal lobe examination—non-dominant hemisphere

Unilateral spatial neglect

Ask the patient to mark the middle of a horizontal line. Displacement of the centre towards the side of the brain lesion (generally right hemisphere) indicates neglect. Target cancellation tests can also be used. This is where a patient is asked to circle every 'a' on a page or something similar. Only one side of the page will be attended to.

Crossed response test

Ask patient to move the limb opposite the one that is touched (motor neglect).

Dressing apraxia

Ask the patient to take off a jumper or other item of clothing. Turn it inside out and ask the patient to put it back on the right way.

Paper cutting

Ask patient to use a pair of scissors to cut out a shape from a piece of paper.

The visual system examination

This section will detail the examination of the eye and cranial nerves II, III, IV, and VI. A thorough history is necessary to understand the patient's range of visual symptoms. These may include drooping eyelids, blurred vision, double vision, 'seeing things', visual loss (transient or persistent, partial, or complete), abnormal movements of the visualized world, eye pain, headache, or orbital pain. In this section we will provide an examination example that avoids missing the most important eye signs.

The neuro-ophthalmological examination should include:

1. *Visual acuity*

   Optic nerve, chiasmal, optic tract lesions, and ocular pathology can all influence visual acuity. This is assessed with corrected vision or refractive vision, like the patient's own glasses or a pin hole. The standard is the Snellen chart that measures vision at a distance of 6 metres. This is expressed as a fraction (distance in metres from chart/distance in metres at which letters should be seen). If the acuity is reduced but is correctable with refraction; this is due to an ocular defect. If the acuity is not correctable, then it signifies a problem in the visual pathway. If the patient is unable to see the largest print, the chart can be brought closer or assessed by finger counting, perception of hand movements, or perception of light.

2. *Colour vision*

   This is most useful for assessing the optic nerve function. It is assessed by using Ishihara plates and scored in each eye individually by the number of plates correctly identified. The speed of identifying the plate should also be considered when comparing the eyes. Remember that 8% of males and 0.5% of females may have X-linked recessive congenital colour deficiency or dyschromatopsia. In these patients the loss of colour vision will be bilateral with normal visual acuity and fields. A cruder method of assessing colour vision is to ask the patient to look at a coloured target like a red cap and in the affected eye it may seem faded or 'washed out'.

3. *Visual field testing*

   Visual fields are tested to direct confrontation and each eye is assessed individually. The patient should fixate on the examiner's nose and cover each eye in turn. This test can detect hemianopia, quadrantanopia, altitudinal, and central field defects. With the eye covered ask the patient if all the parts of the examiner's face are clear, or if there are parts that are blurred or missing. Ask the patient to count fingers in each quadrant.

   Peripheral fields are best assessed with a white hat pin, whereas central fields and blind spots should be tested with a red hat pin. The latter is assessed against the examiner's blind spot by moving the pin. Visual field defects are mapped out according to the patient's description. Abnormalities are illustrated as follows (see Fig. 2.5) and can localize the defect in the visual pathway All patients with a suspected visual field

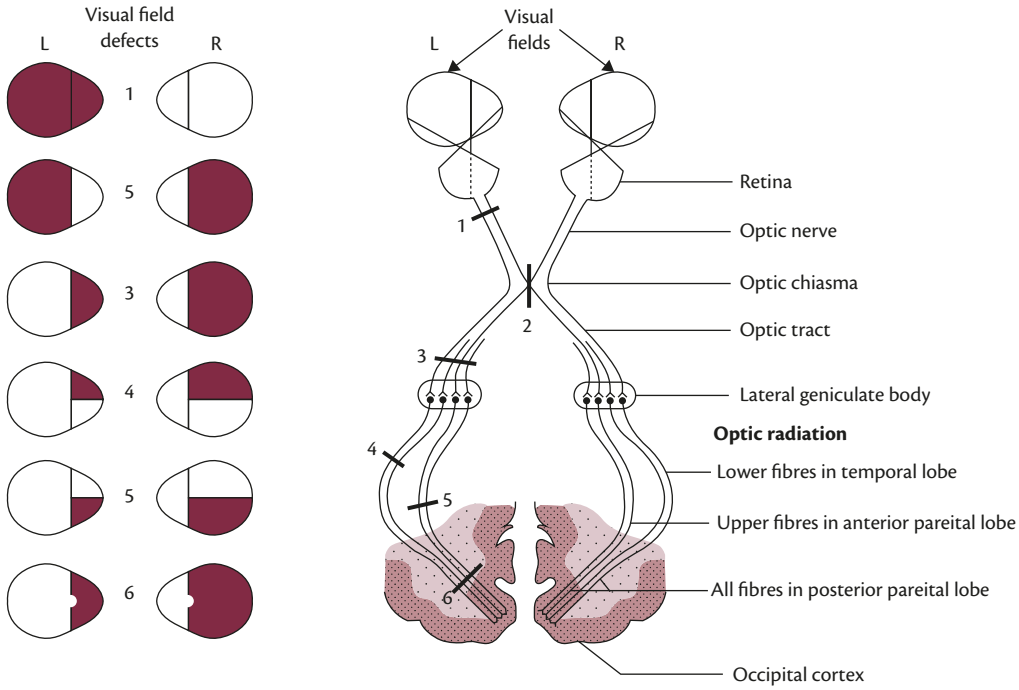

Fig. 2.5 Assessment of visual fields and localization of defects.
From: *Macleod's Clinical Examination*, Ninth edition figure 7.8 page 211, J. Munro and C.R.W. Edwards.

Box 2.6 Parinaud's syndrome

- Impairment of upgaze
- Large irregular pupils that do not react to light but can accommodate (light-near dissociation)
- Eyelid abnormalities—lid retraction or ptosis
- Impaired convergence
- Nystagmus retractorius

defect should have formal perimetry for accurate localization and monitoring. Macular sparing with ischaemic occipital lobe lesions relates to the dual blood supply to the occipital pole from both the middle cerebral artery as well as the posterior cerebral artery.

4. *Pupils*

The pupillary light reaction pathways include the optic nerve (afferent) and the parasympathetic component of the third cranial nerve (efferent). Accommodation arises from the frontal lobes (afferent) and the parasympathetic component of cranial nerve III (efferent).

Inspect first for anisocoria, and then ask the patient to fixate on a distant target and then test the direct and indirect light reflexes, the pupillary reactions to accommodation and finally perform the swinging light test.

4.1 *Size*

The examination of the pupils should first be conducted in room light, if the anisocoria is greater in light than in dark, the parasympathetic system is abnormal, and the larger pupil is abnormal. A cranial nerve III paresis, Adie's pupil, or damaged iris sphincter are examples of the parasympathetic pathway. Then examine for anisocoria in dim light, if this is greater in dim light, a sympathetic dysfunction is present and the smaller pupil is abnormal. Horner's syndrome is a manifestation of a sympathetic disorder. If the anisocoria is the same under both conditions, it is not indicative of a neurological problem.

Conditions that impair light response but do not affect accommodation (light-near dissociation) include Parinaud's syndrome (Box 2.6), neuro-syphilis, diabetes mellitus, Adie's pupil, bilateral optic neuropathy, and aberrant regeneration of cranial nerve III.

4.2 *Light response (direct and indirect)*

Shine a bright light in each eye, and observe the pupils for speed and magnitude of constriction (see Fig. 2.6). If the pupil does not react normally to light, examine the response by viewing a near target. Again, check for speed and magnitude of constriction to a near target and the speed of dilatation when looking at a distant target.

4.3 *Swinging light test*

To perform this test the lights should be dimmed while the patient should fixate on a target in the distance. Swing the light from eye to eye for about a second at a time. Look for the initial movement in each pupil (normally constriction). To diagnose a relative afferent pupil defect (RAPD), one pupil should consistently dilate rather than constrict. The presence of a RAPD is indicative of optic neuropathy (Table 2.3).

5. *Ophthalmoscopy*

For the purposes of this chapter we advise that ophthalmoscopy should be performed on all patients to examine for papilloedema that can suggest raised intracranial pressure and optic pallor suggestive of optic atrophy. Systematically examine the optic disc, the bloods vessels, and then the retinal background.

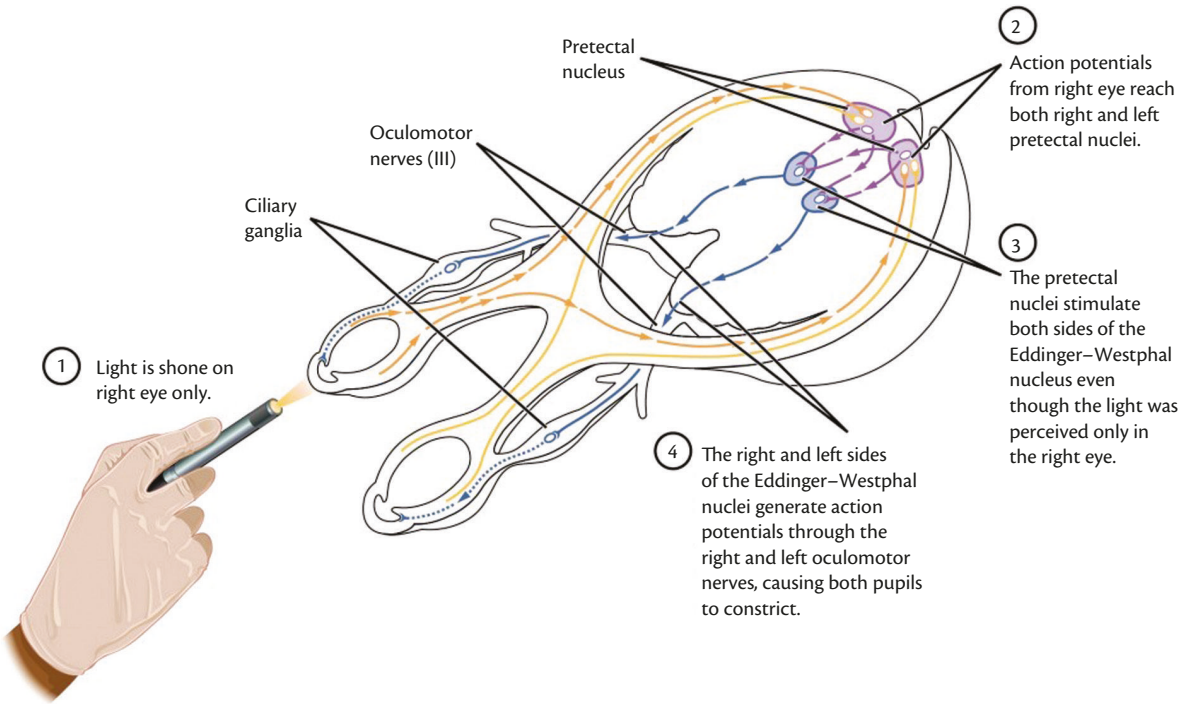

Fig. 2.6 The light reflex.

Authored by: OpenStax College. Provided by: Rice University. Project: Anatomy & Physiology. http://cnx.org/content/col11496/latest/

Table 2.3 Relative afferent pupil defect (Pane, 2007)

Normal pupil		
Light stimulus	**Right pupil**	**Left pupil**
None	•	•
Left	•	•
Right	•	•
Left relative afferent pupil defect		
Light stimulus	**Right pupil**	**Left pupil**
None	•	•
Left	•	•
Right	•	•

This article was published in *The Neuro-ophthalmology Survival Guide*, A Pane, p 379, Copyright Elsevier (2007).

Table 2.4 summarizes some findings that can aid in the localization of lesions that present with visual symptoms using the techniques described so far.

6. *Eye movements*

6.1 *Fixation, nystagmus, and saccades*

Disorders of fixation include nystagmus and saccadic intrusions. The examination will stem from a history of involuntary eye movements or oscillopsia. Congenital fixation disorders are usually asymptomatic and incidentally noticed.

Nystagmus is the rhythmic oscillation of the eyes. Start the examination with eyes in the primary position, then different positions of gaze. Note the fast phase of the nystagmus and the direction or if it is pendular. Also note if the nystagmus is similar in both eyes and if there is a latent component or increased nystagmus with one eye covered. Different types of nystagmus can aid in localization of pathology as summarized in Table 2.5.

Assessing how rapidly and accurately patients can fixate on an eccentric target by testing saccades can expose a subtle internuclear ophthalmoplegia or sixth cranial nerve palsy. It is tested by asking the patient to look at two different objects on either side of the patient's head. The patient is asked to alternate gaze between the objects. Note saccadic initiation, velocity, and accuracy. This can be either too small (hypometric) or too large (hypermetric).

6.2 *Eye movements and cranial nerves III, IV, and VI*

Eye movements include saccades controlled by the frontal lobe, pursuit (the slow movement that facilitate fixation on a moving object) that is controlled by the occipital lobe, the vestibulo-ocular reflex (that allows compensation of eye position for movement of the body or head) controlled by the cerebellar vestibular nuclei and convergence (fixating on an object close to the face) that is controlled by the midbrain. Input from the different control centres have to be integrated to allow synchronous eye movement. The medial longitudinal fasciculus (MLF) in the midbrain runs between the nuclei of cranial nerves III and IV in the midbrain and VI in the pons. The eye muscles are the lateral rectus controlled by cranial nerve VI, the superior oblique controlled by cranial nerve IV, and all the rest are controlled by cranial nerve III.

6.2.1 *Cranial nerve III palsy (oculomotor nerve)*

A complete palsy is a triad of ptosis, a large and unreactive pupil, and the eye position of 'down and out' (Fig. 2.7). Pupil sparing implies that the deeper nerve fibres have been affected most likely from ischaemia. The parasympathetic fibres lie circumferentially on the outside of the nerve and are more commonly affected by compressive causes, classically a posterior communicating artery aneurysm.

Internuclear ophthalmoplegia is the result of a lesion of the MLF. The patient has dysconjugate eye movements; there is incomplete adduction of one eye and jerky nystagmus of the other eye on abduction when testing lateral gaze. It is described as left-sided when there is failure of left adduction when looking to the right (Fig. 2.8). The horizontal conjugate gaze centre resides in the paramedian pontine reticular formation at the level of the fifth cranial nerve nucleus. On an attempt to move the eyes in a horizontal direction, the abducting eye is able to move (VI) but the signal to the third nerve is unable to pass through the MLF to the third nerve is nucleus and there is a failure of adduction. The resulting diplopia may underlie the nystagmus in the abducting eye as there is an attempt to overcome this. The vertical gaze centre resides in the rostral interstitial nucleus of the MLF (riMLF) at the level of the third nerve/superior colliculus.

Table 2.4 Localization of lesions in the visual system (see Beck and Smith, 1988)

	Optic nerve	Optic chiasm	Optic tract	Temporal lobe	Parietal lobe	Occipital lobe
Visual acuity	Normal or reduced	Normal or reduced	Normal or reduced	Normal	Normal	Normal
Colour vision	Normal or reduced	Normal or reduced	Normal or reduced	Normal	Normal	Normal
Visual field	Central scotoma	Bitemporal	Homonymous incongruous	Homonymous superior	Homonymous inferior or complete	Homonymous exquisitely congruous
Relative afferent pupil defect	Present	Present or absent	Present or absent	Absent	Absent	Absent
Disc pallor	Present or absent	Present or absent	Present or absent	Absent	Absent	Absent

Beck & Smith, *Neuro-Ophthalmology: A Problem-Oriented Approach*, 1e, Little Brown & Co, USA, Copyright © 1987.

Table 2.5 Types of nystagmus and neurological localization

Type of nystagmus	Localization
Down beat	Craniocervical junction
Periodic alternating	Craniocervical junction
Gaze-evoked	Vestibular, cerebellum
Up beat	Cerebellum, medulla
Seesaw	Diencephalon, mesencephalon
Torsional	Central vestibular
Convergence–retraction	Dorsal midbrain
Rebound	Cerebellum

Beck & Smith, *Neuro-Ophthalmology: A Problem-Oriented Approach*, 1e, Little Brown & Co, USA, Copyright © 1987.

6.2.2 *Cranial nerve IV palsy (Trochlear nerve)*

This presents with diplopia on looking down and head tilt away from the side of the palsy with no clear squint (Fig. 2.9). The pupil of the affected eye may lie slightly higher than the normal eye, but this is not obvious.

On suspecting a fourth nerve palsy, it is useful to ask the patient to look at a horizontal object (e.g. the top of the door frame alternately with each eye). A trochlear palsy will produce two images angled towards the abnormal side (Fig. 2.10).

6.2.3 *Cranial nerve VI palsy (Abducens nerve)*

This presents with diplopia with two images with horizontal separation (Fig. 2.11). There is a squint, diplopia away from the weak muscle. The pupil is normal.

7. *Lid position*

Inspect for the eyelid position, contour, and measure the palpebral fissures keeping the eyes in the primary position. The upper lid usually covers 1 mm of the cornea, more than that indicates ptosis. Also examine for variable ptosis in different directions of gaze as seen in congenital ptosis and Duane's syndrome. Fatigable ptosis (>2 mm after 2 minutes) on up gaze is suggestive of neuromuscular weakness such as myasthenia gravis.

8. *Orbits*

Finally, during inspection of the orbits one should look for proptosis, enophthalmos, or ocular injection. One should stand behind the patient to assess proptosis looking down over the forehead. A Hertel exophthalmometer provides a more accurate measurement. It may be useful to auscultate over the closed eyelid for a bruit that could signify a carotid-cavernous fistula.

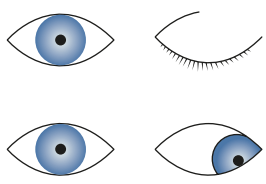

Fig. 2.7 Left third nerve palsy.
From Fuller, G. (2004) *Neurological Examination Made Easy*, 3e, Churchill Livingstone, p. 88, Fig 9.4.

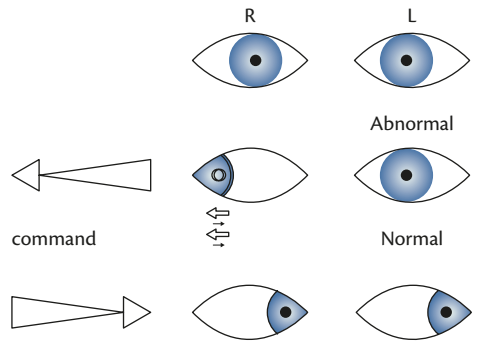

Fig. 2.8 Left internuclear ophthalmoplegia.
From Fuller, G. (2004) *Neurological Examination Made Easy*, 3e. Churchill Livingstone, p. 88, Fig 9.6.

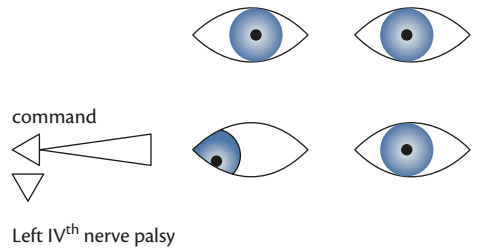

Fig. 2.9 Left fourth nerve palsy.
From Fuller, G. (2004) *Neurological Examination Made Easy*, 3e. Churchill Livingstone, p. 88, Fig 9.4.

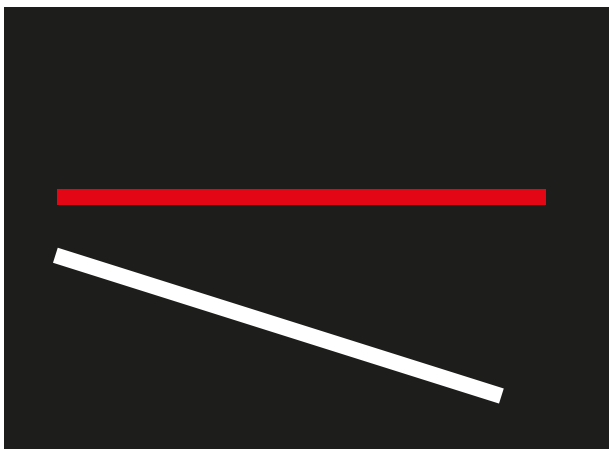

Fig. 2.10 'Door frame' test of patient with left fourth nerve palsy—two images pointing to abnormal side.

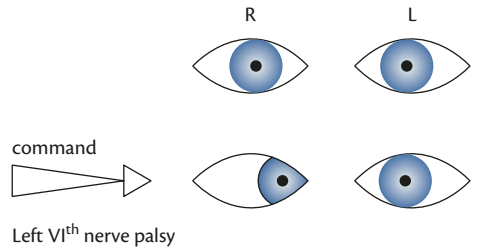

Fig. 2.11 Left sixth nerve palsy.
From Fuller, G. (2004) *Neurological Examination Made Easy*, 3e. Churchill Livingstone, p. 88, Fig 9.4.

Examination of the cranial nerves

This section will include the examination of the cranial nerves not discussed in the section on eye examination.

1. Cranial nerve I (olfaction). Ask if the patient has noticed any change in smell. Examine with two different smells (e.g. coffee or orange). Olfactory test kits are available.
2. Cranial nerve II (typically acuity, fields, and pupillary function). A complete examination would also include fundoscopy, assessment of blind spot, and colour vision.
3. Cranial nerves III, IV, and VI (eye movements).
4. Cranial nerve V (sensation to the face and muscles of mastication). The trigeminal nerve has both motor and sensory components: the maxillary division is the nerve of the first branchial arch derivatives. The motor examination is performed by palpating the muscles of mastication when the patient clenches the jaw and look for jaw movement when asked to open the mouth against resistance. Also tap the jaw jerk. The sensory examination is performed by testing all three divisions of the trigeminal nerve (ophthalmic, maxillary, and mandibular divisions) with light touch. Lastly, perform the corneal reflex (afferent limb Va, efferent limb VII) by gently touching the cornea with a small piece of cotton wool. The approach to the cornea should be lateral to the field of vision. An alternative method is to gently blow in the eye and assess response. Also note the normal conjunctival reaction of lacrimation and injection.
5. Cranial nerve VII (facial expression and taste to anterior two-thirds of the tongue). The facial nerve innervates the muscles of facial expression, stylohyoid, stapedius, and the posterior belly of the digastric muscle, and is the nerve of the second branchial arch (Fig. 2.12). When facial weakness occurs it is important to decide if the weakness is upper (UMN) or lower motor neuron

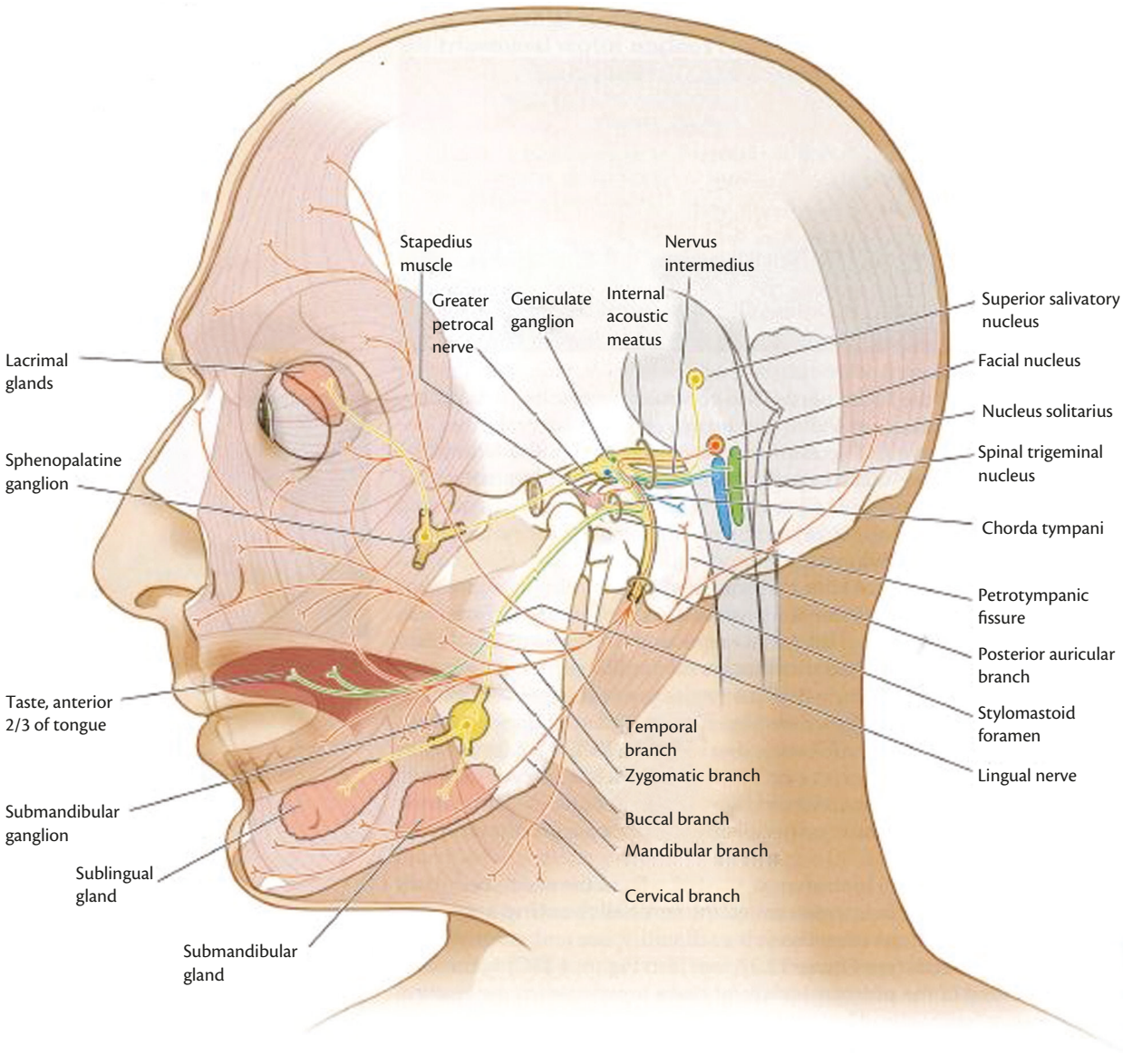

Fig. 2.12 Facial nerve—motor, parasympathetic, and special sense innervation.
Blumenfeld, Hal. (2002) *Neuroanatomy through Clinical Cases*. Sunderland, Massachusetts: Sinauer. Fig 12.10, chapter 12 p. 480.

(LMN). The different clinical features are explained by the bilateral innervation from the nuclei of the facial nerve supplying the superior facial muscles. Firstly, look for asymmetry in facial movement, which can be very subtle: just a hint of incomplete eye closure, slow blinking, or delay in a grin. Then ask the patient to raise the eyebrows (frontalis, temporal branch), close the eyes tightly (orbicularis oculi, zygomatic branch), blow out the cheeks (buccinators) or whistle (orbicularis oris, both buccal branch), show your teeth (zygomaticus major, buccal or marginal mandibular branch), wrinkle the chin (mentalis, marginal mandibular branch), and wrinkle the neck (platysma, cervical branch). The severity of facial palsy is classified using the House–Brackmann scale (see Chapter 24 on the surgical management of cerebellopontine angle lesions).

In UMN weakness the forehead is seen to be stronger than the lower face, also called sparing of the forehead. Unilateral weakness can be due to vascular lesions, demyelination, tumours, or brain stem lesions. Bilateral weakness can be due to pseudobulbar palsy or motor neuron disease.

In LMN weakness, the lower face is seen to be as weak as the forehead. Bell's palsy is a common cause of this and is usually worst within 12 hours from the onset and can be associated with pain around the mastoid, loss of taste, and hyperacusis. Other causes of LMN facial weakness are pontine lesions, cerebellopontine angle lesions, and parotid tumours. Causes of bilateral LMN facial weakness are disorders of the neuromuscular junction like myasthenia gravis, motor neuron disease, myopathies, neurosarcoidosis, or Guillain–Barré syndrome.

6. Cranial nerve VIII (auditory and vestibular nerves). The auditory examination is conducted by testing each ear individually. Cover the ear on the opposite side of the ear being tested. Test the hearing by rubbing your fingers together or whispering. If there is reduced hearing, perform Rinne's and Weber's tests. For these tests you will need a 512 Hz tuning fork. Rinne's test compares bone versus air conduction. The tuning fork is struck and the base is placed on the mastoid process (bone conduction). When the tone disappears, the tuning fork prongs are placed over the external auditory meatus (air conduction). The normal response is for the tone to reappear when the tuning fork is moved in front of the external auditory meatus (i.e. air conduction is better than bone conduction, AC>BC). This reflects the amplification provided by the tympanum and middle ear ossicles. Weber's test involves striking the tuning fork and placing the base over the midline over the forehead. The tone should be heard equally in both ears. If it localizes to one side this can reflect a sensorineural hearing deficit on the contralateral side, or a conductive hearing loss on the ipsilateral side with an increased sensitivity in that ear. These tests can be difficult to interpret and the formal investigation is pure tone audiometry, and with sensorineural hearing loss imaging of the internal auditory canal.

   To examine vestibular function, examine the gait and look for nystagmus. Other tests of value are the Hallpike's test used in patients with positional vertigo. This is performed with the patient sitting up, then turning the head to one side, lie the patient back quickly with their head extended, the examiner should support the patient's head. Observe for nystagmus, associated delay, and also if it fatigues. Ask if the patient experiences vertigo. Repeat this on both sides. If the nystagmus is fatigable and delayed, this is in keeping with peripheral vestibular disturbance such as benign paroxysmal positional vertigo. If not fatigable, this is caused by a central abnormality. Unterberger's test is performed by asking the patient to stand facing the examiner with their arms stretched out in front of him. Ask the patient to close their eyes and march on the spot. Watch for any rotation. Patients turn to the side of vestibular pathology. Only perform this if the patient is able to stand safely. Romberg's test is to assess proprioceptive loss, not specifically balance or vestibular function.

7. Cranial nerve IX and X (palatal movement, swallow, and gag reflex). The glossopharyngeal and vagus nerves are examined together. Firstly, listen to the voice quality for evidence of bulbar weakness, then ask the patient to cough. Inspect the position of the uvula and then ask the patient to say 'Aah'. If there is weakness, the uvula will deviate away from the side of the lesion. The gag reflex is rarely performed and should not be performed if there is any doubt about their safety to swallow as there is potential for aspiration. Video fluoroscopy is safer in such patients.
8. Cranial nerve XI (power to sternocleidomastoid and trapezius). The accessory nerve is examined by testing the power of the trapezius muscles by asking the patient to shrug their shoulders, noting any asymmetry in the initial movement and on inspection. Winging of the scapula may be seen with weakness of trapezius (although serratus anterior palsy from damage to the long thoracic nerve is more common). Test the power and bulk of the sternocleidomastoid muscles by asking the patient to rotate the head to the opposite side against resistance.
9. Cranial nerve XII (tongue power and movements). Examination of the hypoglossal nerve should start with inspection of the tongue lying in the floor of the mouth. Note any wasting or fasciculations. When the patient is asked to protrude the tongue, it will deviate towards the weak side or the side of the unilateral lesion. The speed and fluidity of the movement will be affected in bilateral pyramidal lesions. Power is assessed by asking the patient to press against resistance from the examiner's finger on the outside of the cheek by pressing the tongue firmly on the inside of the same cheek.

Examination of autonomic function and dysfunction

An understanding of how the autonomic system is organized is required to interpret clinical signs that may be encountered during head and neck examination.

Sympathetic fibres arise from the preganglionic cell bodies of the lateral horns of T1–4, form the sympathetic chain and distribute postganglionic fibres via the inferior (to vertebral artery, C7–8), middle (to inferior thyroid artery and C5–6), and superior cervical ganglia (to carotid artery and C1–4). This chain lies posteromedial to the carotid sheath and anterior to the longus muscles. The postganglionic fibres then ride along the external carotid to supply the ciliary ganglion and hence the dilator of the pupil, and the external carotid to supply the submandibular ganglion (submandibular and sublingual glands) and the otic ganglion (parotid gland). A lesion to first, second, or third-order sympathetics will result in Horner's syndrome where there is pupil constriction, partial ptosis, and loss of hemifacial sweating (**Fig. 2.13** and **Box 2.7**). The remainder of the sympathetic

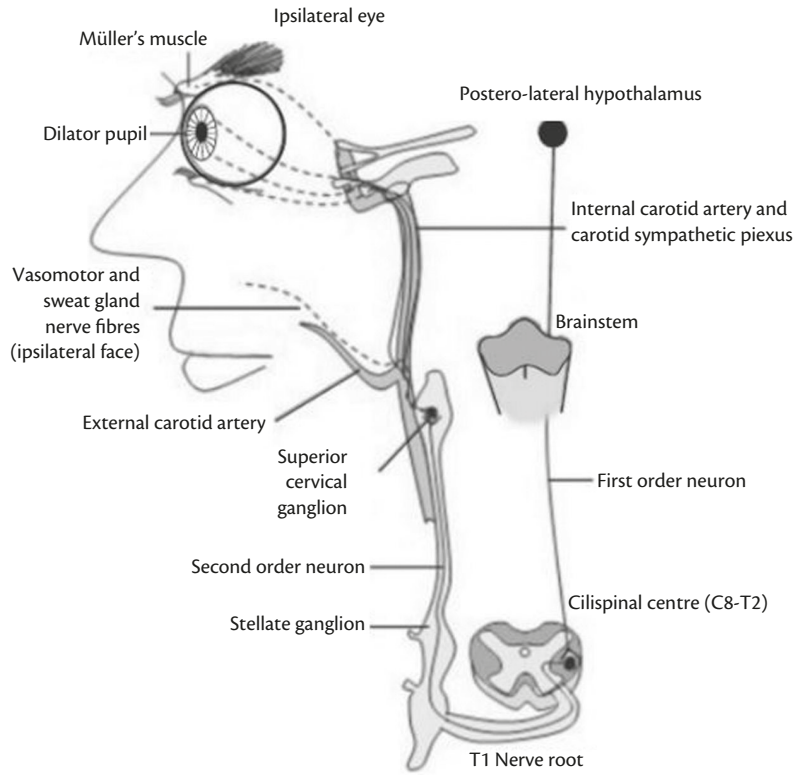

Fig. 2.13 The sympathetic supply of the pupil and causes of Horner's syndrome (Kong, 2007).

supply to the head and neck travels with the internal carotid artery: the deep cervical nerve forms over the petrous segment of the carotid, continues into the middle fossa through the foramen lacerum, and joins the parasympathetic greater superficial petrosal nerve (GSPN) to form the Vidian nerve. The Vidian nerve passes through its own canal to supply autonomic fibres to the pterygopalatine ganglion and distribute parasympathetics with branches of the maxillary division of the trigeminal nerve.

Parasympathetic fibres are carried by four cranial nerves: III, VII, IX, and X. There are four equivalent brainstem parasympathetic nuclei: Edinger Westphal nucleus (III); superior salivatory nucleus (VII); inferior salivatory nucleus (IX); and the dorsal vagal nucleus (X). The vagus provides no cranial parasympathetic supply but provides supply to all the viscera of the thorax and abdomen as far as the midgut (two-thirds of the transverse colon). The preganglionic parasympathetic fibres of the remaining three cranial nerves synapse in four ganglia: ciliary ganglion (III via nerve to inferior oblique); pterygopalatine ganglion (VII via the GSPN); submandibular ganglion (VII via the chorda tympani); and otic ganglion (IX via lesser superficial petrosal nerve). Thus, the facial nerve has two parasympathetic branches that originate at the brainstem level within the nervus intermedius (Fig. 2.12). Crocodile tears syndrome is an uncommon consequence of damage to the facial nerve where there is misdirection of regenerating gustatory fibres to the lacrimal gland resulting in tearing when presented with food.

The postganglionic parasympathetic fibres are then delivered to the target glands by a branch of the trigeminal nerve. Fibres from the ciliary ganglion pass along the short ciliary nerves (branch of nasociliary nerve, Va) to control pupillary constriction and accommodation. Fibres from the pterygopalatine ganglion pass to the lacrimal gland via the zygomaticotemporal (Vb) and lacrimal (Va) nerves. The remainder of the fibres from the pterygopalatine ganglion supply the nose, palate, and nasopharynx sinuses via branches of the maxillary division of the trigeminal nerve. The fibres from the submandibular ganglion supply submandibular and sublingual glands via the lingual nerve (Vc).

Finally, the fibres from the otic ganglion supply the parotid gland via the auriculotemporal nerve (Vc).

Examination of the peripheral nervous system: Upper and lower limbs

The neurological examination of the extremities is based on inspection, assessment of tone, power, reflexes, coordination, and sensation. Having been directed by the history further localization will rely on key examination findings (e.g. confirmation of long tract signs in the patient with suspected myelopathy, correlating deficits in corresponding myotomes and dermatomes in radiculopathy, testing spinothalamic versus dorsal column function in possible syringomyelia, differentiating signs of peripheral neuropathy versus radiculopathy in brachialgia or sciatica, and so on). Understanding the differences between upper and lower motor neurone signs is of course crucial. With this in mind there should be a logical process of elimination, the order of which is open to personal choice and circumstances.

Box 2.7 Differential diagnoses for Horner syndrome

First-order neuron lesions

Arnold–Chairi malformation
Basal meningitis (e.g. syphilis)
Basal skull tumours
Cerebrovascular accident/lateral medullary syndrome
Demyelinating disease (e.g. multiple sclerosis)
Intrapontine haemorrhage
Neck trauma
Pituitary tumour
Syringomyelia

Second-order neuron lesions

Pancoast tumour
Birth trauma with injury to lower brachial plexus
Cervical rib
Aneurysm/dissection of aorta, subclavian, or common carotid artery
Central venous catheterization
Trauma/surgical injury (radical neck dissection, thyroidectomy, carotid angiography, coronary artery bypass graft, upper spine chiropractic manipulation)
Chest tube insertion
Lymphadenopathy (e.g. Hodgkin's disease, leukaemia, tuberculosis, mediastinal tumours)
Mandibular tooth abscess
Lesions of the middle ear (e.g. acute otitis media)
Neuroblastoma
Lumbar epidural anaesthesia

Third-order neuron lesions

Internal carotid artery dissection
Cluster/migraine headaches
Carotid artery thrombosis
Carotid-cavernous fistula
Herpes zoster
Orbital apex tumour
Idiopathic

Box 2.8 Gait abnormalities

- Hemiplegic—spastic leg traces a semicircle due to fixed plantarflexion and extension at the knee
- Diplegic—narrow-based, scissoring gait often due to cerebral palsy
- Myelopathic—broad-based clumsy gait
- Equine—high stepping gait seen in patients with foot drop due to L5 radiculopathy or common peroneal palsy
- Myopathic—waddling gait with pelvis dropping on alternating sides
- Parkinsonian—slow little steps *marche à petits pas*
- Cerebellar—veering uncontrolled gait
- Magnetic—feet seem to be stuck to the floor, seen in normal pressure hydrocephalus

Inspection

There should be an initial general inspection noting features such as abnormal posturing, or preferential use of one limb over another. Stigmata of related systemic disease such as rheumatoid arthritis may be apparent. Assessment of gait may be done at this point. Characteristic pathological gaits point to particular neuroanatomical disorders (Box 2.8). Heel-toe (tandem) walking and Romberg's test are useful adjuncts. Classically, Romberg's test is positive only with disorders of proprioception. Notably, this is not a test of cerebellar function as ataxia would be present with or without closing the eyes with cerebellar disorders. Inspection should continue with examination for atrophy of muscle groups, fasciculations, tremors, and scars such as previous carpal tunnel decompression.

Tone and reflexes

The resistance of muscle groups across a joint is a result of a complex system involving feedback from muscle spindles and Golgi tendon organs, monosynaptic reflexes with agonist and antagonist alpha motor fibres, inhibitory supraspinal control, and processing via the cerebellum. Tone can be decreased (hypotonia) or increased (spasticity or rigidity). Spasticity is a velocity dependent increase in muscle tone in response to a passive stretch, with exaggerated tendon jerks, in association with other features of the upper motor neurone syndrome (Lance, 1980). At the end of range of movement there is often a characteristic 'give' (clasp knife). Rigidity is not velocity or force dependent and lacks any 'give'. Spasticity is more often associated with corticospinal damage whereas rigidity is generally extrapyramidal in origin. Assessment may be by gentle internal and external rolling of the leg, brisk raising of the knee, or pronation/supination at the wrist.

The deep tendon reflexes are tests of a monosynaptic arc. The afferent neurone is stimulated by activity of a Golgi tendon organ; the efferent neurone is an alpha motor neurone. The most frequently tested reflexes are the biceps (C5), supinator (C6), triceps (C7), knee (L3/4), and ankle (S1) jerks. The patient should be in a relaxed posture. A tendon hammer should be used to briskly strike the tendon. If absent, reinforcement can be used by asking the patient to clench the teeth or by interlocking the fingers against resistance.

Specific tests of upper neurone dysfunction include Hoffmann's sign, the plantar response, and clonus. A positive Hoffmann's sign is when quickly flicking the distal phalanx of the middle finger downwards causes flexion of the thumb. Clonus should be tested with the knee flexed, and anything more than five beats of the ankle is pathological.

Power

Muscle groups may be tested in several ways. One can ask the patient to maximally contract the muscle and then attempt to counteract it (isometric). Alternatively, one can attempt to counteract the muscle group through a range of motion (isotonic). The Medical Research Council (MRC) scale provides a reproducible grading system (see Table 2.6). The emphasis placed on examining different muscle groups will depend if one is looking for pyramidal weakness, long tract disease, radiculopathy, or a peripheral nerve problem. When

Table 2.6 MRC grading of power

Grade 5	Normal power
Grade 4	Submaximal movement against resistance
Grade 3	Movement against gravity but not against resistance
Grade 2	Movement with gravity eliminated
Grade 1	Flicker of movement
Grade 0	No movement

Used with the permission of the Medical Research Council.

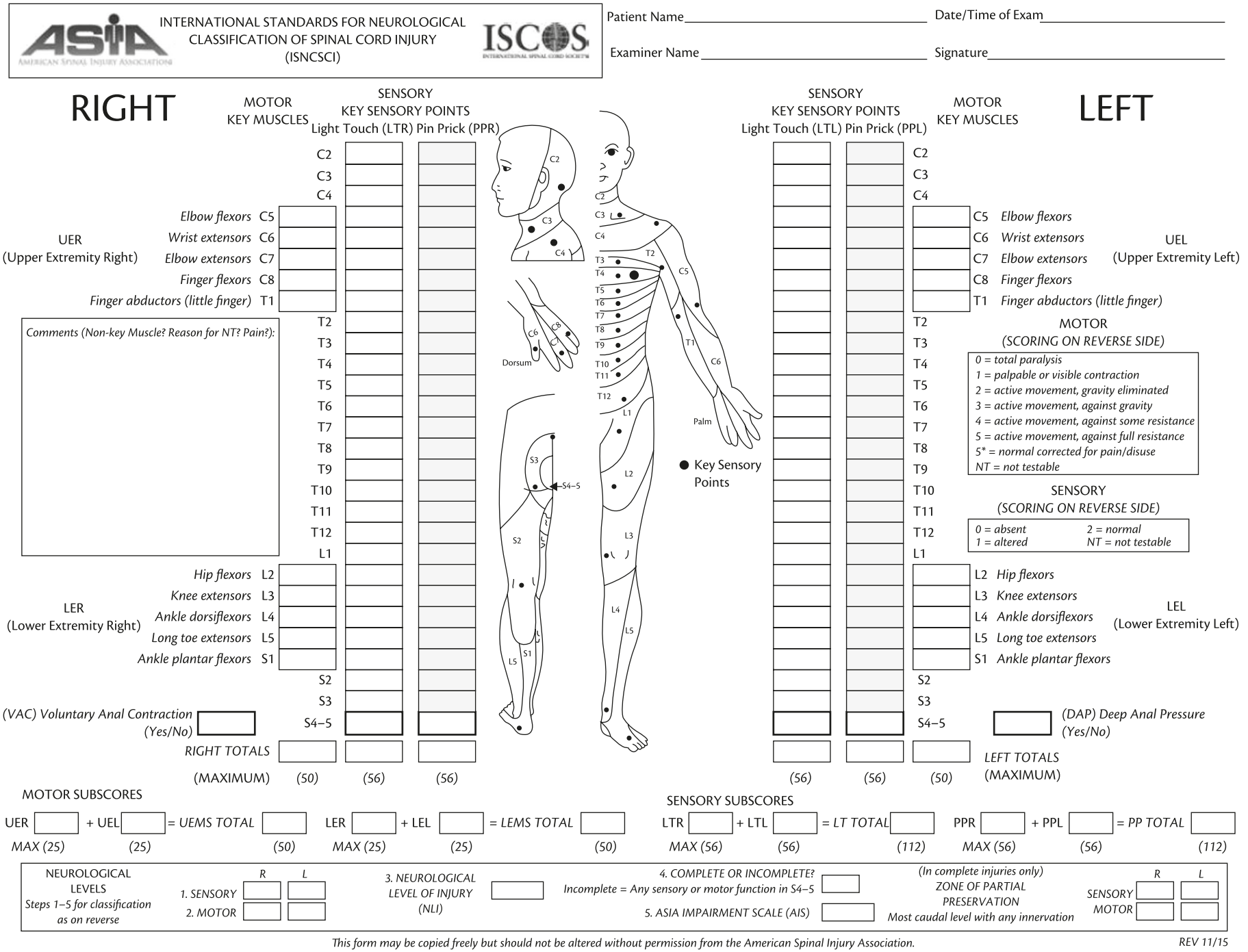

Fig. 2.14 International standards for neurological classification of spinal cord injury workbook.

testing the nerve roots or level of cord dysfunction, the American Spinal Injuries Association workbook (ASIA, 2015) provides an excellent, logical schema (Fig. 2.14). For each level, a particular action is specified to test individual nerve roots.

Sensation

As for the motor examination, sensation should be tested either in a radicular manner or according to peripheral nerve distribution (Fig. 2.15). In addition to peripheral localization, there are different modalities to be considered. Importantly, one should remember that discriminative light touch, proprioception, vibration, and two-point discrimination are conducted through large fast-conducting fibres in the dorsal columns. Pinprick (superficial pain), and temperature are conducted through smaller, slower fibres in the spinothalamic tracts. Again, the ASIA chart is an invaluable guide as to the optimal points for testing sensation. An exact point on the skin is indicated where light touch and pin prick should be tested. It is vital to compare one side against the other as one proceeds. Areas of hypoaesthesia or hyperaesthesia should be carefully mapped out. Asking the patient to close their eyes may provide additional objectivity.

On testing joint position sense, it is important to remember that the patient may be able to tell the direction of motion by how pressure is exerted on a digit. One should, therefore, ensure that the thumb or the great toe are held side to side rather than above and below. Should proprioception be lost, one should test the next proximal joint.

Examination techniques for some common peripheral neuropathies are detailed in Boxes 2.9, 2.10 and Table 2.7.

Putting it all together

As one progresses with the history and examination the information should constantly be distilled, therefore refining the line of questioning and narrowing the focus of examination. Eventually, one has to draw these disparate pieces of information together, make sense of them, and attempt to identify the most likely anatomical source of the patient's complaint and potential pathological processes that may have caused it. Once this point has been reached, it is necessary to decide on whether further investigations are required and what they might consist of.

In the course of this decision-making process, one needs to be rigorous in ensuring strictest objectivity.

> Doctors … are more interested in patients they can help, and diseases they can cure, than the ones they can't. There is, therefore, a tendency for them to make the diagnosis fit their skills or even . . . to have a vested interest in inventing illnesses which they can cure. (Handy, 1990)

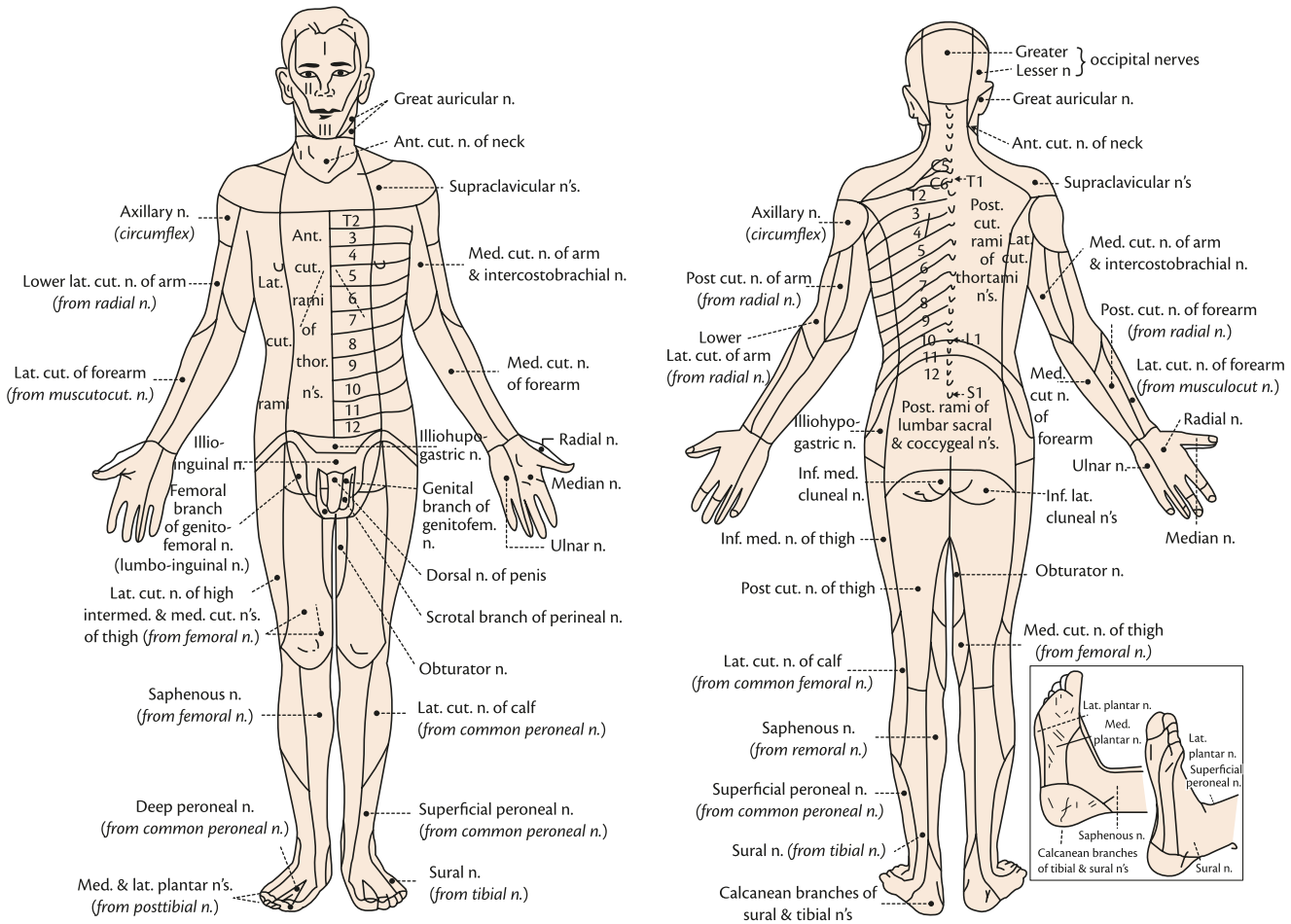

Fig. 2.15 Cutaneous distribution of peripheral nerves (Harrison and Kasper, 2015).

Box 2.9 Examining for carpal tunnel syndrome

- Atrophy of thenar eminence
- Test opposition of thumb by making an O sign
- Test abduction of thumb, lay back of hand down and point thumb upwards
- Splitting of sensation of the ring finger—more sensation on ulnar side
- No loss of sensation in central palm as the palmar cutaneous branch runs above flexor retinaculum
- Phalen's sign (good predictive value)
- Tinel's sign (poor predictive value)
- Absence of benediction sign (attempts to make fist, but thumb and index finger remain extended)—this is due to more proximal compression of median nerve

Box 2.10 Examining for ulnar neuropathy at the elbow

- Wasting of first dorsal interosseous muscle and hypothenar eminence
- Wartenberg's sign—little finger remains abducted, has a tendency to catch on pockets
- Test finger abduction
- Ulnar paradox—ulnar claw hand seen with ulnar nerve damage at the wrist, not present with more proximal lesion at the elbow
- Froment's test—test of adductor pollicis, the only muscle supplied by the ulnar nerve in the thenar eminence. With hands supine ask patient to hold onto piece of paper. Flexion of the thumb on withdrawing the paper indicates positive test
- Tender and enlarged ulnar nerve in the ulnar groove, positive Tinel's test
- Splitting of sensation of the ring finger—more sensation on radial side
- Remember to rule out C8 radiculopathy, Pancoast's tumour, and thoracic outlet syndromes (look for Horner's syndrome to help differentiate)

Table 2.7 Clinical features differentiating L5 radiculopathy and common peroneal palsy[a,b]

	L5 radiculopathy	Common peroneal palsy
Pattern of weakness	Foot inversion (tibialis posterior, the foot invertor, supplied by L4 and L5 via tibial nerve, *not* the peroneal nerve) Hip abduction (gluteus medius and minimus supplied by L4/L5/S1 via superior gluteal nerve)	Foot eversion
Nerve root tension signs	On hip flexion	On ankle inversion
Tinel's test at fibular neck	Negative	Positive

[a] Always remember central causes for foot drop, especially a parafalcine meningioma pressing on the motor cortex.

[b] For peripheral causes the frequencies are as follows: peroneal neuropathy (46%); lumbar radiculopathy (15%); sciatic nerve disorder (5%) (Jeon, 2013).

In considering a patient for an operation there is always a balance to be struck. What are the risks of surgery versus the risk of doing nothing? A clear understanding of natural history is required just as much as the potential complications of a particular operation.

The history and examination provide the foundation stones of patient management. What one does with this information must be guided by our knowledge of neurosurgical conditions. This is described in subsequent chapters.

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3

Overview of neuroimaging

Tomasz Matys, Daniel. J. Scoffings, and Tilak Das

Introduction

The development of computed tomography (CT) (Hounsfield, 1995) and magnetic resonance imaging (MRI) (Mansfield and Maudsley, 1977; Lauterbur, 1989) in the last 40 years has revolutionized neuroimaging, overcoming the limitations of previously used methods that relied on the demonstration of displacement of intracranial vessels or ventricles, and instead allowing the direct visualization of intracranial pathology (Hoeffner et al., 2012). The first clinical CT examination was performed on a patient with a brain tumour and it could be argued that no other field of medicine has benefited more from the further development of cross-sectional imaging techniques than neuroscience. Refinement of MRI and nuclear medicine methods, with the introduction of positron emission tomography (PET) in particular, has allowed for imaging of selected aspects of central nervous system function, such as blood flow, tissue microenvironment, and metabolism. Future progress will no doubt include continuing improvement in the spatial and soft tissue resolution of anatomical imaging and extending the application of functional methods, but also hopefully clinical translation of the full scope of molecular imaging, allowing visualization of specific cellular and molecular events underlying the disease process in addition to its pathological and functional sequelae (Hoffman and Gambhir, 2007; Massoud and Gambhir, 2007).

In this chapter we discuss current neuroradiology imaging modalities that are useful in neurosurgical practice. Due to space constraints, information regarding the underlying physical principles is limited to the basics, while more comprehensive descriptions can be found elsewhere (Allisy-Roberts and Williams, 2007). We focus here on the general usefulness and limitations of neuroradiological methods rather than the imaging manifestations of individual disease processes, which are discussed elsewhere in the relevant chapters of this book. The interested reader can find further information in dedicated neuroradiology monographs (see Nadgir and Yousem, 2016).

Principles of imaging

Radiographs and fluoroscopy

Radiographs ('plain X-rays') are produced by passing a collimated beam of X-rays through a patient onto an image receptor, traditionally a cassette containing combination of a fluoroscopic screen and radiographic film, but in modern practice a digital detector is typically used. The tissues in the patient's body attenuate the X-ray beam to differing degrees so that the intensity of the X-rays reaching the detector varies across its surface. In this way radiographs can distinguish between air (black), fat (dark grey), soft tissue and water (light grey), and bone (white). The radiographic image is also a two-dimensional representation of a three-dimensional structure and it is typically necessary to obtain images in different (often orthogonal) projections to infer the position of a given abnormality within the patient.

With the increasing availability of CT and MRI, the role of conventional radiographs in the assessment of patients with neurosurgical disease has reduced, but they retain a role in certain circumstances. The advantages of radiographs include their ease of acquisition, low cost, widespread availability, the ability to obtain images at the bedside, and also to obtain a degree of dynamic information by acquiring radiographs with the patient in different positions (e.g. standing, in flexion, and extension of the spine). Although they have high spatial resolution, a major disadvantage of radiographs is their limited soft tissue resolution. Indications for radiographs include assessment of the continuity of the extracranial components of ventricular shunts, the position and integrity of spinal implants and prostheses, and the follow-up of patients with spinal fractures in whom loss of normal alignment or progression of vertebral body compression is suspected. Radiographs are less sensitive than CT in the detection of spinal fractures and have a very limited role in the primary assessment of suspected spinal injury. Flexion-extension radiographs are often used in evaluation of potential instability in patients with degenerative or spondylolytic spondylolisthesis.

Fluoroscopy provides real-time images of the area of anatomical interest by passing a continuous or pulsed X-ray beam through the patient onto an image-intensifier, most commonly using a C-arm apparatus which can be rotated and positioned around the patient to provide the desired view. Uses of fluoroscopy include the identification of the correct level for spine surgery, monitoring the placement of spinal fixation devices or prostheses, and the performance of lumbar puncture in patients in whom bedside lumbar puncture (LP) has been unsuccessful due to obesity or degenerative changes.

Computed tomography

CT basics and techniques

Introduced into clinical practice in 1973, CT was the first diagnostic imaging modality to enable direct visualization of the brain (Wolpert, 2000). Similar to plain film radiography, CT is based on a differential attenuation of X-rays by tissues, but uses a differently collimated beam sweeping around the patient in a circular fashion and reaching a large number of individual detectors; the image is then created using mathematical reconstruction algorithms. In brief, when an X-ray photon travels along a particular line through the patient's body, it experiences energy loss that depends on attenuation coefficients of tissues it encounters on its path. By measuring photon energy from multiple directions around the object, it is possible to calculate the attenuation coefficients for each voxel (volume element) within the examined volume. Attenuation coefficient values are then converted into more convenient-to-use radiodensity values ('CT numbers') calculated in relation to water and air, and expressed in Hounsfield units (HU). The scale of CT numbers ranges from –1000 HU (air) to over 3000 HU (cortical bone), with 0 HU being the attenuation of distilled water. Typical values for different central nervous system (CNS) tissues are given in **Table 3.1**.

The way in which the multidirectional information is obtained and the speed of acquisition have dramatically changed with technological advances, from a pencil-like X-ray beam translating along a slice in the original machine to a fan-shaped beam and increasing number of detectors along the circumference of the gantry and across multiple rows (Ginat and Gupta, 2014). An important development in CT scanning technology was the advent of helical or spiral CT, where the data is obtained in continuous fashion while the patient moves smoothly through the gantry and the X-ray tube rotates, continuously tracing a spiral trajectory around the body. While this mode of acquisition allowed significant improvements in body CT scanning, it introduces unwanted 'windmill artefacts' (Barrett and Keat, 2004), and sequential CT may still be preferable for head imaging. In neuroradiological applications, helical CT does allow excellent quality CT angiography for the evaluation of neck and intracranial vessels, as well as isotropic resolution volumetric reconstructions that can be visualized in any arbitrary plane.

To convert raw CT data into a useful image, the matrix of radiodensities is displayed as shades of grey. From the range of the Hounsfield scale, possible CT numbers span up to 4000 levels of radiodensity, yet the human observer can theoretically perceive approximately 720 shades of grey in optimal conditions (Kimpe and Tuytschaever, 2007) and this is much lower in practice. It is therefore not possible to map the entire dynamic range of CT numbers to greyscale at the same time, necessitating the use of a 'window' centred at a certain level and of particular width to display a suitable fragment of this range. Values of radiodensities within the window are displayed as shades of grey, while values below and above the window boundaries are displayed as black and white, respectively. Because most tissues of interest in the brain lie in the range of 0 to 100 HU, these are optimally depicted using a window centred at a level of around 40 HU and width of 80 HU (Fig. 3.1A). As the radiodensity of acute haemorrhage lies close to the upper limit of the standard window, haemorrhage appears bright and is readily apparent; it is however difficult to appreciate blood immediately adjacent to bone. Using 'subdural windows' with at a slightly higher level and a larger width (e.g. L/W 70/200) makes acute blood better distinguishable from the adjacent bone (**Fig. 3.1B**). Setting the window level to negative values allows differentiation of fat from air. To interrogate bone detail, the window needs to be set to a higher level and width (e.g. L/W 500/3000, **Fig. 3.2**).

One of the most important parameters that affect image quality is the kind of mathematical reconstruction algorithm, also referred to as a reconstruction kernel or filter. Use of different kernels changes the balance between spatial resolution and image noise. A smooth kernel generates images with lower noise and better low-contrast detectability more suited to brain examinations, at a cost of reduced spatial resolution. A sharp kernel generates images with high spatial

Table 3.1 Attenuation values of the main tissues/materials in neuroimaging

Material	Hounsfield units
Acute blood	56 to 76
Air	–1000
Bone	1000 to 3000
Calcification	140 to 200
Cerebrospinal fluid	0
Fat	–30 to –100
Grey matter	32 to 41
White matter (centrum semiovale)	23 to 34

This table was adapted from *Neuroradiology: The Requisites*, David Yousem, Robert Zimmerman, Robert Grossman, Copyright Elsevier (2010).

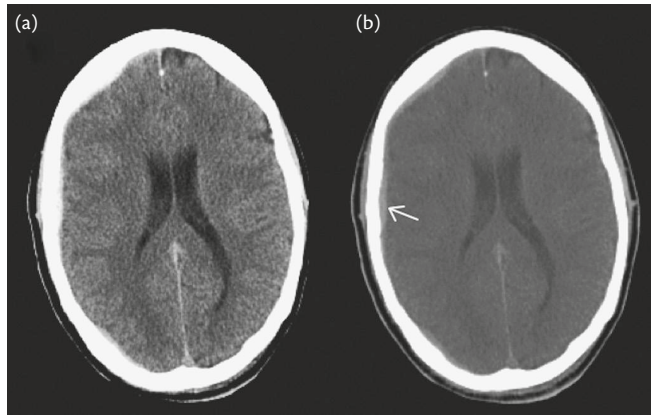

Fig. 3.1 Standard window (A, level/width 40:80) provides good differentiation of the grey and white matter but high-density haemorrhage adjacent to the skull is difficult to appreciate. Widening the window (B, 'subdural window' 70:200) makes the thin right sided subdural haemorrhage (arrow) more conspicuous.

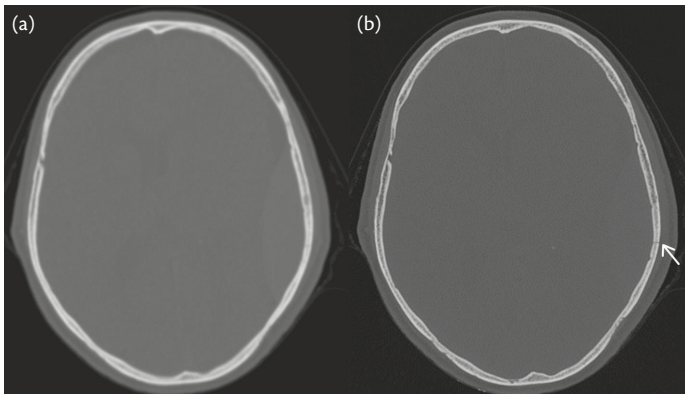

Fig. 3.2 Image of the skull seen on bone window (L/W 500:3000) reconstructed using standard (A) and bone (B) kernel. Hairline fracture of the left squamous temporal bone is much more conspicuous using bone kernel reconstruction (arrow).

resolution better suited to the assessment of bony structures. Use of bone kernel is essential for detection of fractures (Fig. 3.2) and should be a part of any CT performed in the context of trauma, as well as sinonasal and temporal bone examinations.

CT contrast media and risks

Iodinated contrast media have historically been the contrast agent of choice for X-ray and CT applications due to high attenuation of iodine compounds thanks to its high atomic number (Lusic and Grinstaff, 2013). In CT brain imaging, contrast media are used to detect areas of blood-brain barrier breakdown, where contrast medium leaks into parenchyma, or to opacify blood vessels in CT angiography, including venography.

The risks of iodinated contrast media include allergic reactions and contrast-induced acute kidney injury. To minimize this, it is important to identify susceptible individuals (Box 3.1) and take appropriate preventative steps (Iodinated Contrast Media Guideline, Royal Australian and New Zealand College of Radiologists).

The current standard is to use non-ionic, low osmolarity compounds. The incidence of severe reactions with this type of media is 0.04% and for very serious reactions is 0.004% (Hunt et al., 2009). A typical adult dose of intravenous contrast medium for head CT is 50 ml of a compound containing 300 mg/ml iodine. Larger amounts are used in angiographic applications. Contrast medium can also be administered intrathecally through a lumbar, cervical, cisternal, or ventricular approach (Nadgir and Yousem, 2016); this may require lower concentration compound approved for intrathecal use, especially in children.

Box 3.1 Risk factors for contrast-induced acute kidney injury (CI-AKI) and allergic reaction to contrast media

Risk factors for CI-AKI

Known kidney disease (including kidney transplant)
Presence of diabetes
Metformin (risk of lactic acidosis)

Risk factors for allergic reaction to contrast media

Previous allergic reaction to iodinated contrast media
Previous significant allergic reactions to other substances or history of eczema
History of asthma
Use of beta blockers

The Royal Australian and New Zealand College of Radiologists. Iodinated Contrast Media Guideline. Sydney: RANZCR; 2018.

Advantages and disadvantages of CT

CT plays an extremely important role in neuroimaging, particularly in the emergency and neurosurgical settings (Nadgir and Yousem, 2016). It is a rapid, easily accessible, and efficient modality for screening patients with major traumatic injury. It has high sensitivity to haemorrhage, particularly in the first 24 hours compared to MRI, and can demonstrate features of raised intracranial pressure and brain herniation, allowing for rapid decision-making in early stages of traumatic injury. For the detection of subarachnoid haemorrhage (SAH), it remains the initial imaging study of choice in suspected cases and can be rapidly followed by CT angiography when SAH is identified. Similarly, it remains a useful technique for assessment of cerebral infarction and, in conjunction with CT angiography and CT perfusion, for guiding thrombolytic therapy in patients with suspected ischaemic stroke (Kidwell and Wintermark, 2010).

For postoperative examinations in both brain and spine, CT is useful in evaluating for complications (such as haemorrhage, infarct, or hydrocephalus), and the position of ventricular drains or other adjuncts. Portable head CT scanners are now available allowing examination at a neurocritical care bed without the need for transporting an unstable patient.

CT venography can often be used as an alternative to MR venography or help with troubleshooting in the case of confounding artefacts on MRI.

CT is the best modality for assessing bone lesions and is essential for the evaluation of skull, skull base, facial, and spine fractures. It is also the technique of choice for primary evaluation of the temporal bones and paranasal sinuses.

CT sensitivity for calcification is helpful with the diagnosis of calcium-containing CNS tumours (e.g. meningioma, oligodendroglioma, craniopharyngioma), metabolic disorders (e.g. hyperparathyroidism), and congenital lesions (e.g. TORCH infections, tuberous sclerosis). Finally, CT myelography is a viable alternative to MR in spine imaging in patients with absolute contraindications to MR imaging.

The use of radiation remains a drawback for CT technology. For a head CT, the average effective dose is approximately 2 millisievert (mSv), compared to an annual background radiation of 2–5 mSv. Other neuroradiological examinations incur higher doses (Table 3.2). Possible effects of radiation can be divided into deterministic (predictable and depending on cumulative radiation dose, for example, cataract due to lens irradiation), and stochastic (chance-like, for example, induction of malignancy) (Allisy-Roberts and Williams, 2007). The risk of cataract should be taken into account, especially in children (Michel et al., 2012).

In pregnancy, the dose to the fetus from head and neck CT is low and the risk of inducing childhood cancer is thought to be < 1 in 1 000 000. Examinations with direct exposure of the fetus (e.g. spinal CT) result in higher risk (1 in 1000–10 000) and should be avoided (The Royal College of Radiologists, 2009). The administration of iodinated contrast agents carries a theoretical risk of fetal thyroid suppression and thyroid function should be checked in the first week after birth.

Table 3.2 Typical radiation dose in neuroradiological CT-based examinations (Cohnen et al., 2006; Mettler et al., 2008)

Examination	Average dose (range)
CT head	1.7 mSv
CT angiogram head	1.9 mSv
CT angiogram neck	2.8 mSv
CT perfusion cerebral	1.1–5.0 mSv
Comprehensive stroke protocol	Up to 9.5 mSV
CT spine	6 mSV

Data from Cohnen, M et al., Radiation exposure of patients in comprehensive computed tomography of the head in acute stroke, *AJNR. American Journal of Neuroradiology*, volume 27, issue 8, pp. 1741–5. 2006, and Mettler, F.A et al., Effective doses in radiology and diagnostic nuclear medicine: a catalog, *Radiology*, volume 248, issue 1, pp. 254–63. 2008.

Advances in CT technology include attempts to reduce the necessary radiation dose while maintaining acceptable image quality, particularly important for paediatric imaging. The main way of reducing radiation exposure is adapting the dose by changing the tube voltage and current (and therefore X-ray photon energy and beam intensity) according to the patient's size, weight, and specific imaging application. A different method that allows scanning with a lower dose while maintaining image quality is replacement of the conventional reconstruction technique, known as filtered back projection, with iterative reconstruction (IR) which requires additional computation time but generates images with lower noise and higher spatial resolution, as well as reduced beam hardening and metal artefacts. Although the effects are more pronounced in body imaging, dose reductions have also been demonstrated for head imaging (Kilic et al., 2011; Mirro et al., 2016). The images appear subjectively different between the two reconstruction techniques and IR is therefore still under clinical evaluation.

Magnetic resonance imaging (MRI)

MRI basics and techniques

MRI takes advantage of the phenomenon of nuclear magnetic resonance, inherent to nuclei that have a magnetic moment due to an uneven number of protons or neutrons; in practice this mainly involves imaging of hydrogen nuclei (^{1}H) containing a single proton. MRI is based on a radiofrequency signal that is emitted when protons aligned with a strong magnetic field are tipped out of alignment by an externally applied radiofrequency pulse and then return to equilibrium (**Fig. 3.3**). The emitted signals are read out in a spatially ordered fashion and reconstructed into an image reflecting the magnitude of signal in a given voxel. The type of excitation pulse, time at which the signal is read out, and interval between excitations can be varied resulting in a different contrast in the final image (Allisy-Roberts and Williams, 2007). Two principal MRI sequences provide image weighting that depends on T_1 or T_2 relaxation times of the tissue (**Table 3.3**); appearances of the brain on the most commonly used sequences are shown in **Figure 3.4**. Images weighted according to proton density (PD) can be obtained together with T_2-weighted images with no additional scanning time required; they provide good contrast between the grey and white matter, and are of value in certain situations, but are not universally used in neuroradiology. Water has high signal on T_2-weighted sequences, and because most pathological processes are associated with increased water content (oedema), they appear hyperintense on T_2 weighted images. Fat is hyperintense on T_2-weighted images but unlike water it shows high T_1 signal. Besides fat, T_1 hyperintensity can also be due to melanin, protein-rich fluid, calcification, and gadolinium-chelate contrast agents (see later). Haemorrhage has complex appearances on MRI with combination of signal intensities dependent on the degradation phase of blood products (**Table 3.4**).

Signal in MRI can be produced using spin echo or gradient recalled echo sequences (Bitar et al., 2006; Allisy-Roberts and Williams, 2007). Spin echo provides better signal-to-noise ratio and is generally preferable, but slower than gradient echo. Acquisition of large volumetric datasets, required for example by neurosurgical navigation systems, is therefore performed using a variant of the gradient echo sequence. An important feature of gradient echo sequences is the lack of compensation of magnetic field inhomogeneities, resulting in its sensitivity to local susceptibility effects. This is used in practice for detection of haemorrhage, as the local susceptibility effect caused by iron in haemosiderin results in a very low signal with 'blooming' on gradient echo sequences. Even better depiction of haemosiderin, for example, microhaemorrhages in the setting of traumatic brain injury, is achieved with susceptibility weighted imaging (SWI), a high-resolution 3D velocity-compensated long echo time gradient echo sequence (Di Ieva et al., 2015). Gradient echo sequences are also used in other situations in which image contrast depends on susceptibility effects such as dynamic susceptibility contrast perfusion imaging and blood-oxygenation level dependent methods.

Image contrast in MRI can be varied using suppression techniques designed to null signal from a specific tissue. In the brain, this is used in fluid-attenuated inversion recovery (FLAIR), which nulls the cerebrospinal fluid signal; it is routinely used with T_2-weighting to make parenchymal T_2 hyperintensity more conspicuous (T_2-FLAIR, usually referred to simply as FLAIR). This should not be confused with a less common T_1-FLAIR sequence, which is used for example to improve grey-white matter contrast that is otherwise reduced at higher magnetic field strengths.

Fat suppression techniques increase conspicuity of fluid signal on T_2-weighted images or contrast enhancement on T_1-weighted images in situations where they could be masked by the presence of fat (such as detection of oedema in the vertebral column or paraspinal soft tissues, or contrast enhancement at the skull base, respectively). Fat suppression can be achieved by short tau inversion recovery (STIR) or spectral saturation. STIR is useful near bone-containing structures (orbit, skull base, sinuses), metallic foreign bodies, and across large fields of view, for example, in spine imaging. STIR is however problematic when combined with contrast medium, when spectral fat saturation is used instead.

Balanced steady state free precession (SSFP) sequences provide high resolution and excellent signal-to-noise ratio with a mixed T_2/T_1-weighting. In neuroimaging, these sequences are usually performed with a heavy T_2-weighting delivering high contrast resolution between cerebrospinal fluid and contained structures, such as the cisternal segments of the cranial nerves and adjacent blood vessels. Balanced SSFP techniques such as fast imaging in steady state (FIESTA) or constructive interference in steady state are therefore useful in investigation of vascular loops as the cause underlying trigeminal neuralgia or hemifacial spasm, as well as in screening for cerebellopontine angle tumours. Other uses include the evaluation of inner ear structures, and identification of cerebrospinal fluid leaks (Saindane, 2015).

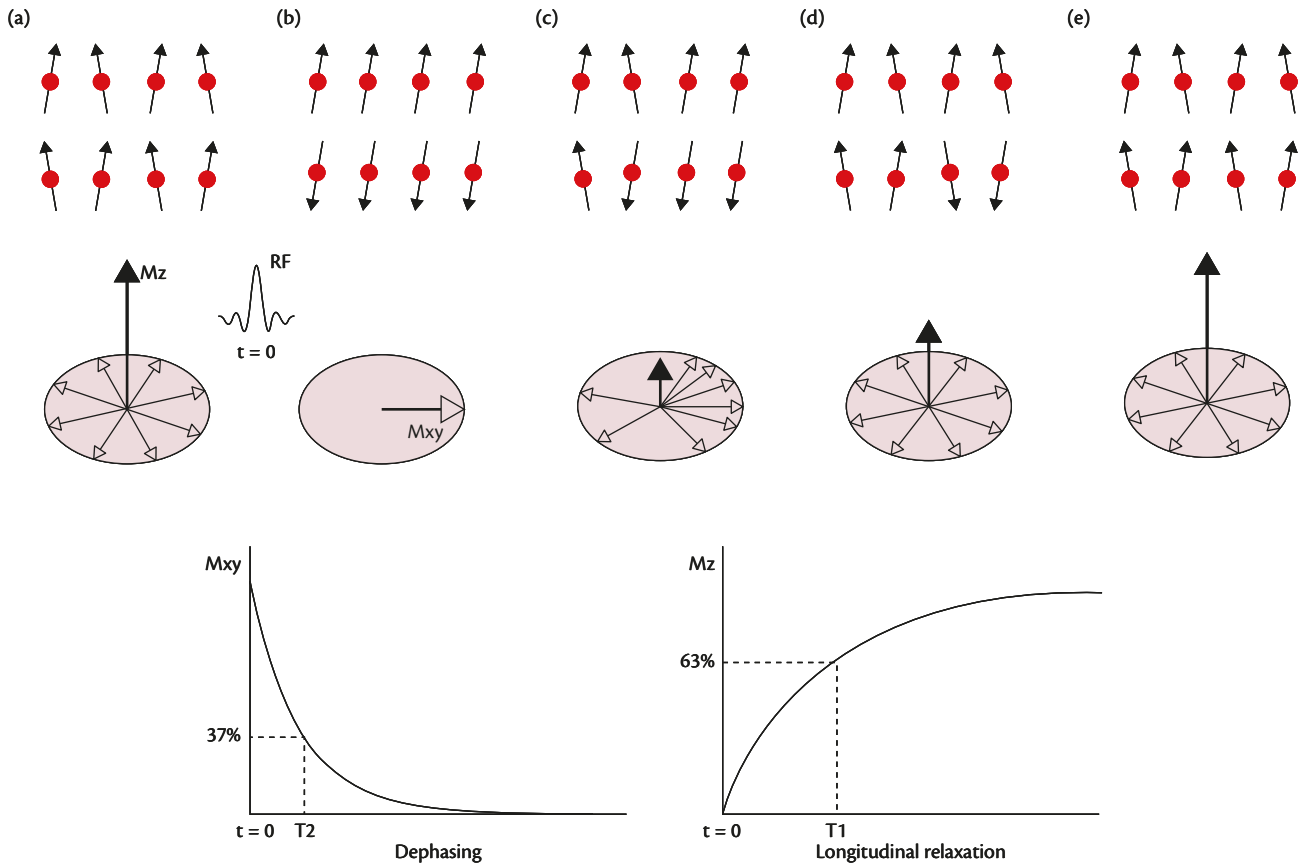

Fig. 3.3 Due to having a charge and spin, protons display magnetic properties and behave like magnetic dipoles. Outside of a magnetic field, the dipoles are randomly distributed and the net magnetization is zero in any direction in space. When placed in a magnetic field, the magnetic dipoles align with the field, either parallel ('spin up') or antiparallel ('spin down') to it, and start to precess (wobble around their axes) with a frequency dependent on the strength of the magnetic field (Larmor frequency). (A) Because a small excess of dipoles (approximately three per million) point 'spin up' their longitudinal magnetization vectors add up creating net longitudinal magnetization Mz. Due to precession, each dipole also creates a transverse magnetization vector rotating in the transverse plane. However, because the dipoles precess in different phases, their transverse magnetization vectors cancel each other and the net transverse magnetization remains zero. (B) Application of an external radiofrequency (RF) pulse turns some dipoles spin down; a so-called 90°RF pulse turns exactly half of the excess dipoles spin down, so now equal numbers of dipoles point in either direction and the net Mz vector is null. The RF pulse also causes synchronization of the phase of precession, so all the dipoles precess together (they achieve phase coherence) and their transverse magnetization adds up to produce a net transverse magnetization vector Mxy, rotating in the transverse plane. (C–E) After the RF pulse ends, within a short time the protons return to their initial state by losing phase coherence (dephasing, resulting in a loss of transverse magnetization Mxy) and by returning to the spin up orientation (longitudinal relaxation, resulting in 'regrowth' of the longitudinal magnetization vector Mz). These processes happen exponentially with time constants T2 and T1, respectively—T2 indicates the time after which dephasing is complete in 63% (so 37% phase coherence remains), and T1 corresponds to the time at which 63% of the longitudinal magnetization has recovered (bottom panels). T2 is always shorter and dephasing is complete (D) before longitudinal relaxation (E). T1 and T2 times depend on the type of the tissue and determine tissue contrast on T1- and T2-weighted sequences. Tissues with short T1 appear bright on T1-weighted sequence, while long T2 results in low signal on T2-weighted sequence (e.g. fat has high signal on T1- and T2-weighted sequences due to short T1 and relatively long T2).

Table 3.3 Signal intensity of different substances and tissues on T1- and T2-weighted MRI sequences

Substance	T1-weighted sequence	T2-weighted sequence
Water/Cerebrospinal fluid	↓	↑
Fat	↑	↑
Air	↓	↓
Cortical bone	↓	↓
Red bone marrow	=/↑	↑
Yellow bone marrow	↑	↑

Diffusion-weighted imaging (DWI) is sensitive to the movement of water molecules. DWI weighting is usually achieved by applying special diffusion-encoding gradients along the three principal spatial directions, and combining the signal into a trace image. Because the DWI trace image has both diffusion weighting and T_2-weighting, apparent hyperintensity can be due to restricted diffusion, or 'shine-through' phenomenon if the underlying area is T_2-hyperintense. It is therefore essential to review the apparent diffusion coefficient map (ADC), which eliminates the effect of T_2 weighting and demonstrates restricted diffusion as low signal intensity. Restricted diffusion may reflect a reduction in the size of the extracellular space that can be a result of cell swelling (e.g. in ischaemic stroke) or high cellularity (e.g. in lymphoma or

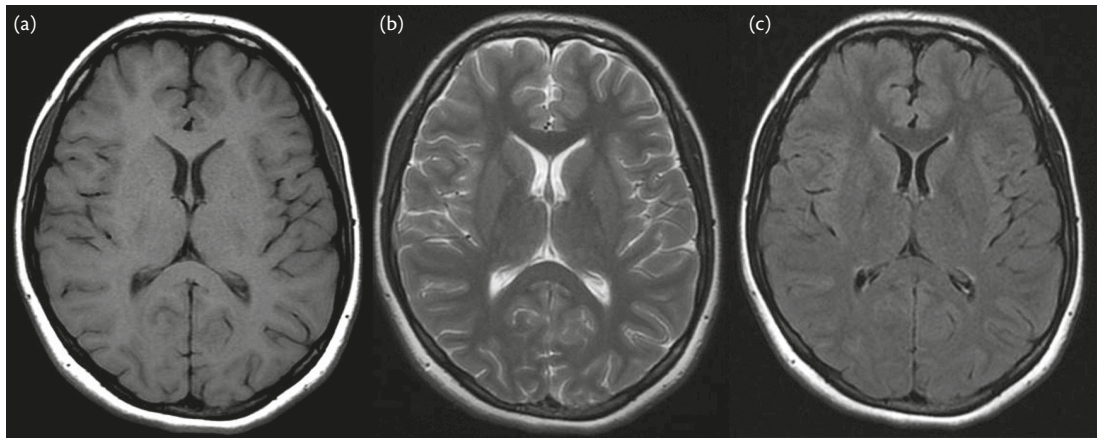

Fig. 3.4 Appearances of the brain on routine MRI sequences. (A) On T_1-weighted image grey matter is darker ('greyer') than white matter. (B) On T_2-weighted image the white matter is darker than grey matter and fluid is hyperintense. (C) T_2-FLAIR show similar contrast between the grey and white matter as T_2-weighted images but the signal from CSF is nulled.

medulloblastoma), as well as in lesions such as cholesteatoma or epidermoid cyst. In neurosurgical practice, the most important application of DWI is differentiation of pyogenic abscess from other ring-enhancing lesions, with the contents of the abscess demonstrating markedly restricted diffusion.

Applying diffusion gradients in at least six different directions underlies diffusion tensor imaging (DTI) which enables calculation of the predominant direction of diffusion in a given voxel. Because the movement of water is relatively unrestricted along the white matter tracts, DTI allows calculation of nerve fibres' direction and reconstruction of white matter tracts (DTI tractography), useful in neurosurgical planning (Waldman et al., 2009; Saindane, 2015). DTI also enables estimation of several measures of diffusion anisotropy with promising results in imaging and prognostication in traumatic brain injury (Hulkower et al., 2013) and high-grade gliomas (Price et al., 2007; Yan et al., 2016).

Functional MRI (fMRI) is based on blood oxygen level dependent (BOLD) effect resulting from different magnetic properties of oxyhaemoglobin (diamagnetic) and deoxyhaemoglobin (paramagnetic). Areas of the cortex with increased neuronal activity demonstrate higher oxygen consumption, but also increased perfusion due to neurovascular coupling; the effect of increased perfusion predominates, and the net result is a relative increase in MRI signal. Different activation paradigms allow the individual mapping of important cortical functions such as sensorimotor cortex and language localization (Stippich and Blatow, 2007).

Table 3.4 Signal intensity of haemorrhage of different stages on T1- and T2-weighted MRI sequences

Haemorrhage stage	Haemoglobin product	T1-weighted sequence	T2-weighted sequence
Hyperacute (<24 hrs)	Oxyhaemoglobin	=	↑
Acute (1–3 days)	Deoxyhaemoglobin	=	↓
Early subacute (3–7 days)	Intracellular methaemoglobin	↑	↓
Late subacute (1–4 weeks)	Extracellular methaemoglobin	↑	↑
Chronic (>1 month)	Haemosiderin	↓	↓↓

Contrast media in MRI

The majority of the contrast media used in MRI are paramagnetic agents based on gadolinium compounds. The pharmacokinetics of these agents are similar to those of iodinated contrast media with rapid passage from the vascular compartment to the interstitial compartment; an exception is gadofosveset, a blood pool agent that binds to albumin and remains in the vascular compartment. Gadolinium compounds do not pass through an intact blood-brain barrier so contrast enhancement is considered reflective of blood-brain barrier breakdown, apart from circumventricular organs, which have an incomplete blood-brain barrier and demonstrate physiological contrast enhancement that should not be mistaken for abnormality (Horsburgh and Massoud, 2013). Contrast enhancement is more conspicuous on MRI than on CT, and is invaluable in characterization of tumours, vascular disease, inflammation, and infection, both in the brain and in the spine.

Gadolinium compounds are generally safe but there are potential side effects associated with the release of unbound gadolinium from its chelates and accumulation in tissues. Nephrogenic systemic fibrosis is a rare but disabling dermopathy resembling scleroderma and eosinophilic fasciitis, first observed in patients on dialysis undergoing gadolinium contrast-enhanced MRI. Most cases were associated with the use of less stable linear agents that are now classified as high risk (Table 3.5). These compounds require renal function monitoring and are contraindicated in patients with glomerular filtration rate (GFR) below 30 ml/min/1.73 m^2, in neonates, and in the perioperative liver transplantation period; breastfeeding should

Table 3.5 Classification of gadolinium-based MRI contrast agents according to the risk of nephrogenic systemic fibrosis

High risk	Medium risk	Low risk
Gadodiamide (Omniscan)	Gadoxetic acid (Primovist)	Gadoteric acid (Dotarem)
Gadoversatamide (OptiMARK)	Gadobenic acid (MultiHance)	Gadoteridol (ProHance)
Gadopentetic acid (Magnevist)	Gadofosveset (Vasovist)	Gadobutrol (Gadovist)

Data from Drug Safety Update Jan 2010, vol 3 issue 6: 3. https://www.gov.uk

be discontinued for at least 24 hours after high-risk agent administration. Similar precautions are recommended but not mandatory for medium- and low-risk agents.

Recently it has been recognized that repeated administration of gadolinium-based contrast agents leads to accumulation of gadolinium in the brain, with the highest concentrations detected in the dentate nucleus and globus pallidus (Kanda et al., 2015b; McDonald et al., 2015). Accumulation of gadolinium is seen in patients receiving the less stable linear, but not macrocyclic compounds (Kanda et al., 2015b), and occurs even in the presence of normal renal function (Kanda et al., 2015a; McDonald et al., 2015). The clinical significance of these findings is however currently unknown.

General application of MRI in neurosurgery

Structural MRI has several advantages over CT and is the investigation of choice in the assessment of intracranial and spinal pathology with the exception of a few specific situations. In structural imaging, MRI provides superior tissue contrast, greater sensitivity to parenchymal abnormalities and contrast enhancement, better demonstration of anatomy, and allows imaging in any plane without using ionizing radiation; further information can be gained by addition of functional sequences. Disadvantages of MRI include long scanning time making it problematic in medically unstable patients and more prone to motion artefacts; therefore CT, with its established value in demonstration of intracranial haemorrhage and fractures, remains the investigation of choice in emergency situations, especially in trauma. CT is also better in demonstrating cortical bone and calcification, and remains more easily available and less costly. Use of MRI can be limited by several safety issues related to the static magnetic field, radiofrequency pulses, and gradient fields. MRI cannot generally be performed in patients with pacemakers, ferromagnetic aneurysm clips, implants, or foreign bodies. Care must be taken when imaging patients with shunt valves, cochlear implants, and heart valves, as well as in pregnancy; departmental practices vary. Finally, claustrophobia may preclude many patients from undergoing the MRI investigation or limit the scan time.

Positron emission tomography (PET)

PET is a nuclear medicine technique that uses tracers labelled with positron-emitting isotopes. The most commonly used radionuclide is fluorine-18 (^{18}F) due to its relatively long half-life that approaches two hours and is sufficiently long to allow transportation from an external cyclotron facility to the imaging centre. Short-lived isotopes require an on-site cyclotron (^{11}C, ^{13}N, ^{15}O) or are produced in a generator (^{68}Ga, ^{82}Rb). In the target organ, positrons emitted by the radionuclides travel a very short distance before interacting with electrons in neighbouring atoms and undergoing annihilation with the emission of two high energy photons that travel in opposite directions, which are detected by a ring array of solid-state scintillator detectors. The image is reconstructed based on the coregistration of pulses between opposite pairs of detectors, allowing placement of the annihilation event along a specific line of response (Fig. 3.5). Time of flight PET (TOF-PET) also measures tiny differences in time of arrival of the two photons to the opposite detectors, allowing more precise placement of the annihilation event to a segment along the line of response. Data needs to be corrected for the attenuation of photons inside the patient; this is achieved by using a rotating radiation source in standalone PET or direct information on attenuation

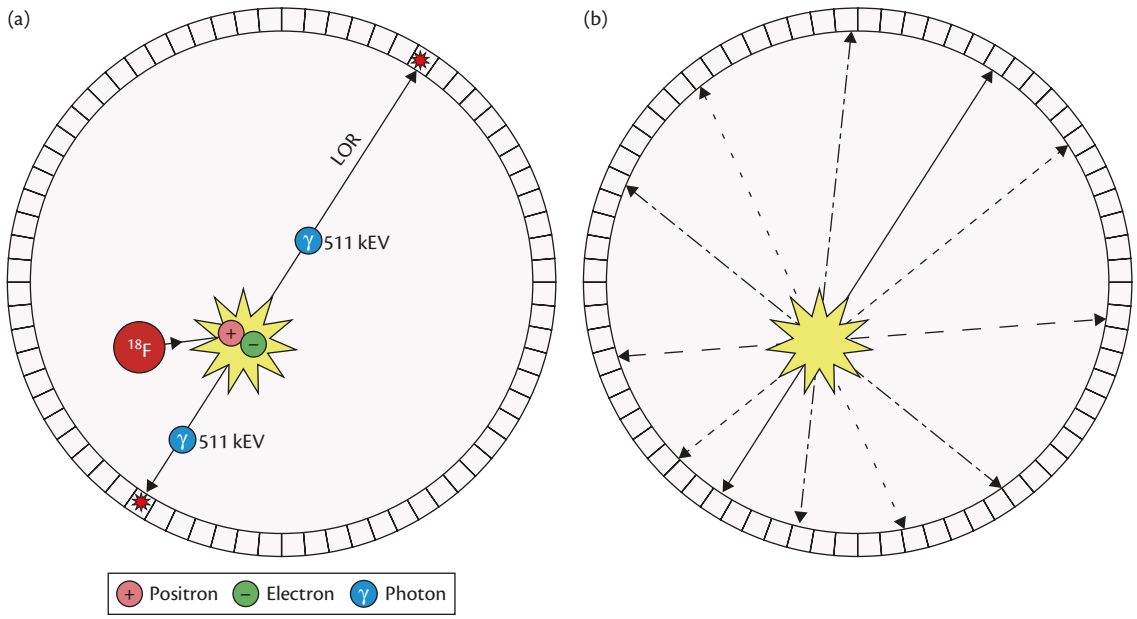

Fig. 3.5 (A) A positron-emitting isotope (most commonly 18F) releases positrons which collide with electrons in the target organ resulting in a series of annihilation events. Each annihilation event results in the emission of two high energy (511 keV) photons travelling in a straight line in opposite directions (at 180° to each other) at the speed of light. The two photons reach a ring of detectors placed around the gantry at the same time (if the annihilation happens in the centre of the gantry) or within a very short time window (if annihilation happens off-centre). The detection of such a coincidence event allows localization of the source of photons somewhere along the line of response (LOR) joining the pair of detectors which registered the photons. In time of flight (TOF) PET the tiny difference in time it takes for each photon to reach the detector for off-centre events is also taken into account, allowing the localization of the annihilation event more precisely along the LOR. (B) As photons produced by a series of annihilation events travel along different lines of response, combining information from multiple detected coincidence events allows localization of the radiation source.

obtained from a CT scan in PET-CT hybrid scanners. Data correction in MRI-PET is more challenging and requires calculation of attenuation values from anatomical MRI images.

PET is extremely sensitive, being able to detect picomolar quantities of tracer labelled with a positron emitter. In theory, any physiologically occurring substance, drug, or receptor ligand can be labelled, making PET the most promising technique for functional and molecular imaging. The most widely used tracer is ^{18}F-fluorodeoxyglucose (^{18}F-FDG), the uptake of which reflects the rate of glucose metabolism. Use of ^{18}F-FDG in the brain is problematic due to high rate of physiologic glucose metabolism; its potential applications include imaging of high-grade brain tumours, anaplastic transformation of low-grade gliomas, differentiation of radiation necrosis from tumour progression, differentiation of lymphoma from toxoplasmosis in immunocompromised patients, as well as detection of focal cortical dysplasia in epilepsy investigation. The armamentarium of PET tracers and range of potential applications in brain imaging is expanding; these are summarized in Table 3.6.

Most PET scanners in clinical use currently are either standalone machines, or PET-CT hybrids. Increasingly, PET-MRI hybrid scanners are becoming available. In view of the superior tissue contrast and resolution of MRI in the brain, integrated PET-MRI has potential advantages in neuroimaging. So far, it has been possible to combine sequential PET and MRI images acquired sequentially on separate scanners but hybrid PET-MRI imaging greatly facilitates such fusion eliminating the need for subsequent coregistration. More importantly, simultaneous acquisition of PET and MRI images could be of value when measuring parameters that undergo temporal changes, such as cerebral perfusion or hypoxia (Catana et al., 2012). These methods are currently largely limited to neuroimaging research, and their clinical usefulness remains to be established.

Other nuclear medicine techniques

Most nuclear medicine techniques use tracers labelled with radioligands emitting gamma radiation. The most commonly used radionuclide is ^{99m}Tc (technetium) due to a combination of optimal half-life, ease of production, and ease of incorporation into radiopharmaceuticals. Other isotopes used in neuroimaging include ^{111}In (indium) and ^{133}Xe (xenon). Emitted gamma rays can be detected using a planar gamma camera or rotating gamma camera in single-photon emission computed tomography (SPECT). Applications of SPECT in neuroradiology include cerebral perfusion measurements with ^{99m}Tc-HMPAO, ^{99m}Tc-ECD, and ^{133}Xe, diagnosis of dementia, identifying seizure focus in epilepsy, dopamine transporter imaging in diagnosis of parkinsonian syndromes, and brain tumour evaluation (McArthur et al., 2011). Planar gamma camera images are obtained in radionuclide cisternography, usually with ^{111}In-DTPA, performed for investigation of hydrocephalus or CSF leaks.

Myelography

Although MRI is the preferred method for examination of most spinal abnormalities, myelography remains indicated in patients who cannot undergo MRI (e.g. because of a pacemaker) and it also has a role in the detection of CSF leak sites in patients with spontaneous intracranial hypotension (Kranz et al., 2016). Iodinated contrast medium is injected into the spinal subarachnoid space, most commonly after lumbar puncture but sometimes after a lateral puncture at C1–2 if lumbar puncture cannot be performed. The puncture is typically done using fluoroscopic guidance and the injection of contrast is monitored by intermitted fluoroscopy to ensure that inadvertent epidural or subdural injection has not occurred. The contrast is then moved along the spinal canal to the appropriate location(s)

Table 3.6 Examples of PET tracers used in neuroimaging

PET tracer	Mechanism of action and applications
^{11}C-methionine, ^{18}F-FET	Transport into the cell via amino acid transporter increased in malignant tumours—characterization of tumour extent, biopsy guidance, treatment planning, response assessment (radiation necrosis, recurrence, pseudoresponse), prognostication; assessment of striatal dopamine pathway (^{18}F-DOPA)
^{18}F-FLT	Uptake correlated with activity of thymidine kinase-1 in proliferating cells—assessment of tumour grade, treatment response, prognostication
^{18}F-FMISO, ^{18}F-FAZA	Accumulation in hypoxic cells—assessment of hypoxia in brain tumours with potential relevance to tumour progression and resistance to treatment
^{11}C-PK11195, ^{18}F-GE180	Binding to translocator protein (TSPO) expressed in activated microglia and cancer cell lines—assessment of microglial activation/inflammation, assessment of tumour grade
^{68}Ga-DOTA-TOC ^{68}Ga-DOTA-TATE	Somatostatin analogues with high uptake in certain intracranial tumours—diagnosis of meningioma, pituitary adenoma, hemangioblastoma, medulloblastoma, PNET
^{11}C-PiB (Pittsburgh compound) ^{18}F-florbetaben, ^{18}F-florbetapir ^{18}F-flutemetamol	Binding to beta-amyloid plaques—diagnosis of Alzheimer disease
^{11}C-PBB3 ^{18}F-FDDNP	Binding to tau protein/neurofibrillary tangles—diagnosis of Alzheimer disease and tauopathies
^{11}C-flumaeznil ^{11}C-diprenorphine ^{11}C-SCH23390 ^{11}C-raclopride	Benzodiazepine receptor ligand—receptor binding studies Opioid receptor ligand—receptor binding studies Dopamine D_1 receptor ligand—receptor binding studies Dopamine D_2 receptor ligand—receptor binding studies
$^{15}O_2$ and [^{15}O] H_2O ^{11}C-leucine, ^{11}C-tyrosine ^{11}C-albumin $^{11}CO_2$, ^{11}C-DMO	Cerebral blood flow, oxygen metabolism Protein synthesis rate Plasma volume pH