NS201C
Anatomy 1: Sensory and Motor Systems

25th January 2017

Peter Ohara
Department of Anatomy
peter.ohara@ucsf.edu
The Subdivisions and Components of the Central Nervous System
Axes and Anatomical Planes of Sections of the Human and Rat Brain
Development of the neural tube

A: Ectoderm, Amniotic cavity
B: Mesoderm, Notochord
C: Neural groove
D: Neural fold, Cut edge of amnion

20 Days: Neural fold, Pericardial bulge, Otic placode
22 Days: Neural plate, Neural groove
23 Days: Somite, Neural fold
25 Days: 1st and 2nd pharyngeal arches, Anterior neuropore
Dorsal and ventral cell groups
Neural crest derivatives: 1
### Environmental Factors Promoting Differentiation of Neural Crest Cells

<table>
<thead>
<tr>
<th>Neural crest derivative</th>
<th>Interacting structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bones of cranial vault</td>
<td>Brain</td>
</tr>
<tr>
<td>Bones of base of skull</td>
<td>Notochord, brain</td>
</tr>
<tr>
<td>Pharyngeal arch cartilages</td>
<td>Pharyngeal endoderm</td>
</tr>
<tr>
<td>Meckel's cartilage</td>
<td>Cranial ectoderm</td>
</tr>
<tr>
<td>Maxillary bone</td>
<td>Maxillary ectoderm</td>
</tr>
<tr>
<td>Mandible</td>
<td>Mandibular ectoderm</td>
</tr>
<tr>
<td>Palate</td>
<td>Palatal ectoderm</td>
</tr>
<tr>
<td>Otic capsule</td>
<td>Otic vesicle</td>
</tr>
<tr>
<td>Dentine of teeth</td>
<td>Oral ectoderm</td>
</tr>
<tr>
<td>Glandular stroma: thyroid, parathyroid, thymus, salivary</td>
<td>Local epithelium</td>
</tr>
<tr>
<td>Adrenal medullary chromaffin cells</td>
<td>Glucocorticoids secreted by adrenal cortex</td>
</tr>
<tr>
<td>Enteric neurons</td>
<td>Gut wall</td>
</tr>
<tr>
<td>Sympathetic neurons</td>
<td>Spinal cord, notochord, somites</td>
</tr>
<tr>
<td>Sensory neurons</td>
<td>Peripheral target tissue</td>
</tr>
<tr>
<td>Pigment cells</td>
<td>Extracellular matrix along pathway of migration</td>
</tr>
</tbody>
</table>
Development of the neural tube 2

(A) Optic vesicle  Rhombencephalon  Cervical flexure  Cranial and spinal ganglia

Mesencephalon  Prosencephalon

(B) Mesencephalon  Pontine flexure  Myelencephalon

Telencephalon  Spinal cord

Cephalic flexure

Five-vesicle stage (5 weeks)

Prosencephalon (forebrain)
- Cerebral hemispheres
  - Cerebral cortex
  - Subcortical white matter
  - Basal ganglia
  - Basal forebrain nuclei

Telencephalon

Diencephalon
- Thalamus
- Hypothalamus
- Epithalamus

Mesencephalon (midbrain)
- Cerebral peduncles
- Midbrain tectum
- Midbrain tegmentum

Rhombencephalon (hindbrain)
- Metencephalon
  - Pons
  - Cerebellum

Myelencephalon
- Medulla

Spinal cord
Timing of development of the neural tube and its derivatives

**Susceptibility to Teratogenesis for Organ Systems**

(Solid bar denotes highly sensitive periods)

<table>
<thead>
<tr>
<th>Precursor Stage</th>
<th>Embryonic Period (weeks)</th>
<th>Fetal Period (weeks)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fertilization to bilaminar disc formation</td>
<td>1</td>
<td>3-6</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>7-8</td>
</tr>
</tbody>
</table>

- **Central Nervous System**
- **Heart**
- **Ear**
- **Eyes**
- **Upper Limb**
- **Lower Limb**
- **Lip**
- **Teeth**
- **Palate**
- **External Genitalia**

**Major Malformations**

**Functional Defects and Minor Malformations**
<table>
<thead>
<tr>
<th>Gestational age (Weeks)</th>
<th>Crown-rump length (mm)</th>
<th>Structure(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>3</td>
<td>cerebral vesicles</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>Optic cup, otic placode (future internal ear)</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>cerebral vesicles, cranial nerve nuclei</td>
</tr>
<tr>
<td>6</td>
<td>12</td>
<td>Cranial and cervical flexures, rhombic lips (future cerebellum)</td>
</tr>
<tr>
<td>7</td>
<td>17</td>
<td>Thalamus, hypothalamus, internal capsule, basal ganglia</td>
</tr>
<tr>
<td>8</td>
<td>30</td>
<td>Hippocampus, fornix, olfactory bulb, longitudinal fissure that separates the hemispheres</td>
</tr>
<tr>
<td>10</td>
<td>53</td>
<td>First callosal fibers cross the midline, early cerebellum</td>
</tr>
<tr>
<td>12</td>
<td>80</td>
<td>Major expansion of the cerebral cortex</td>
</tr>
<tr>
<td>16</td>
<td>134</td>
<td>Olfactory connections established</td>
</tr>
<tr>
<td>20</td>
<td>185</td>
<td>Gyral and sulcual patterns of the cerebral cortex established</td>
</tr>
</tbody>
</table>
A 68 year old woman with hypertension and diabetes develops abrupt onset numbness and tingling on the right half of the face and head and the entire right hemitrunk, right arm and right leg. She does not experience any weakness or incoordination.

**Physical Examination:**
Vitals: T 37.0° C; BP 168/87; P 86; RR 16
Cardiovascular, pulmonary, and abdominal exam are within normal limits.

**Neurological Examination:**
**Mental Status:** Alert and oriented x 3, 3/3 recall in 3 minutes, language fluent.
**Cranial nerves:** CN II-XII intact except for objective loss of all sensation (including fine touch, two point discrimination, pain and temperature) on the right side of the face.
**Motor:** Normal bulk and tone. Strength and reflexes are as follows:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>5/5</td>
<td>5/5</td>
<td>5/5</td>
<td>5/5</td>
<td>5/5</td>
<td>5/5</td>
<td>5/5</td>
</tr>
<tr>
<td>L</td>
<td>5/5</td>
<td>5/5</td>
<td>5/5</td>
<td>5/5</td>
<td>5/5</td>
<td>5/5</td>
<td>5/5</td>
</tr>
<tr>
<td></td>
<td>iliopsoas</td>
<td>Hams</td>
<td>Quads</td>
<td>Tibialis ant.</td>
<td>Gastroc.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R</td>
<td>5/5</td>
<td>5/5</td>
<td>5/5</td>
<td>5/5</td>
<td>5/5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>5/5</td>
<td>5/5</td>
<td>5/5</td>
<td>5/5</td>
<td>5/5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Sensation:** Intact fine touch, two point discrimination, vibration, joint position sense, pain and temperature sensation in the left arm, left leg and left hemitrunk. Complete sensory loss of all modalities in the right arm, right hemitrunk and right leg.

**Coordination:** Normal rapid alternating movements in the upper and lower extremities, and normal finger-to-nose and heel-knee-shin testing.

**Gait:** Normal

Where is the most likely location of the lesion that gives rise to these symptoms?
The Major Components of the Nervous System and Their Functional Relationships

- **Cerebrum, cerebellum, brainstem, and spinal cord**
  - **SENSORY COMPONENTS**
    - Sensory ganglia and nerves
    - Sensory receptors
  - **MOTOR COMPONENTS**
    - VISCERAL MOTOR SYSTEM
      - Autonomic ganglia and nerves
    - SOMATIC MOTOR SYSTEM
      - Motor nerves
  - **INTERNAL AND EXTERNAL ENVIRONMENT**
  - **EFFECTORS**
    - Smooth muscles, cardiac muscles, and glands
    - Skeletal muscles
The somatosensory and motor pathways

**Fine touch pathway**
- Thalamus
- Primary somatosensory cortex
- Medulla
- Secondary sensory neuron
- Vibration, proprioception, light touch
- Dorsal root ganglion
- Spinal cord

**Nociceptive pathway**
- Thalamus
- Primary somatosensory cortex
- Secondary sensory neuron
- Pain, temperature, crude touch
- Dorsal root ganglion
- Spinal cord

**Motor pathway**
- Primary motor cortex
- Precentral gyrus (motor cortex)
- Posterior limb of internal capsule
- Pyramidal decussation
- Upper motor neuron
- Lower motor neuron
- Cervical
- Thoracic
- Lumbar
- Sacral
- Skeletal muscle
Somatosensory pathways

1st order: dorsal root ganglion

2nd order: Spinal cord or brainstem

3rd order: Thalamus

Cortex
**Somatosensory pathways**

- **Spinothalamic path** – Pain and temperature.
- **Dorsal column medial lemniscal** – fine touch, proprioception, vibration.

---

**Medial lemniscus**

**Dorsal column nuclei**

**Dorsal columns**

**Spinothalamic tract**
Spinal cord and dorsal root ganglia
Spinal cord and sensory component of peripheral nerves
Les dermatomes correspondent à l'innervation sensitive des nerfs spinaux.

Copyright docteur Richard Martzloff-Encyclopédie médicale Vulgaris
Spinal cord tracts

- Dorsal horn (sensory)
- Ventral horn (motor)

- Gracilis fasciculus
- Cuneatus fasciculus
- Dorsal spinocerebellar tract
- Lateral corticospinal tract
- Lateral reticulospinal tract
- Medial reticulospinal tract
- Ventral spinocerebellar tract
- Anterolateral system
- Ventral corticospinal tract
- Medial tectospinal tract
- Lateral tectospinal tract
- Vestibulospinal tract
Brainstem

- midbrain
- pons
- medulla
- upper cervical cord
Dorsal view of brainstem and spinal cord

Superior colliculi
Cut cerebral peduncles
Dorsal column nuclei
Dorsal columns
Dorsal roots
1. All sensory information for the face is carried in the three branches of the Vth cranial nerve that has three sensory divisions (V1, V2, V3).

2. All 1st order sensory neurons have their cell body in the trigeminal GANGLION (equivalent to the dorsal root ganglion in the spinal cord).

3. Our rules for 1st, 2nd and 3rd order sensory neurons still apply. The second order neurons are in the trigeminal NUCLEUS.
Sensory pathway: **Thalamus**
Thalamus: medial view

- Medial wall of thalamus
- Massa intermedia
- Mammillary body
- Hypothalamus
Thalamus: Coronal view

- Thalamus
- Basal ganglia
- Internal capsule
Lateral view cortex

Central sulcus
Primary sensory cortex (S1)
Lateral fissure
Ratunculus
Topographic organization of primary motor cortex
Corticospinal tract

- Cortex
- Internal capsule
- Midbrain
  - Cerebral peduncle
- Middle pons
  - Collaterals to reticular formation
  - Pontine fiber bundles
- Middle medulla
- Pyramid
- Caudal medulla
  - Pyramidal decussation
  - Lateral corticospinal tract
  - α motor neuron
Corticospinal tracts (Lateral and Ventral)
The somatosensory and motor pathways

Fine touch pathway

Nociceptive pathway

Motor pathway
Sensations begin with the stimulation of receptors that are specialized parts of the axon and are located throughout the body. Each sensory modality is associated with a particular receptor.
C-fiber variation

Rexed laminae
Axons (nerve fibers) have a range of sizes and conduct electrical impulses at different speeds.

<table>
<thead>
<tr>
<th>Sensory function</th>
<th>Receptor type</th>
<th>Afferent axon type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proprioception</td>
<td>Muscle spindle</td>
<td>Aβ</td>
</tr>
<tr>
<td></td>
<td>Axon: 13–20 μm, Myelin: 80–120 m/s</td>
<td></td>
</tr>
<tr>
<td>Touch</td>
<td>Merkel, Meissner, Pacinian, Ruffini</td>
<td>AB</td>
</tr>
<tr>
<td></td>
<td>cells: 6–12 μm, AB: 35–75 m/s</td>
<td></td>
</tr>
<tr>
<td>Pain, temperature</td>
<td>Free nerve endings</td>
<td>Aδ</td>
</tr>
<tr>
<td></td>
<td>Axon: 1–5 μm, Aδ: 5–30 m/s</td>
<td></td>
</tr>
<tr>
<td>Pain, temperature, itch</td>
<td>Free nerve endings</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>Axon: 0.2–1.5 μm, C: 0.5–2 m/s</td>
<td></td>
</tr>
</tbody>
</table>

*NEUROSCIENCE, Fourth Edition, Table 9.1*
Neurotransmitters/neuromodulators/circuits in the dorsal horn
The gate theory

Dorsal horn spinal cord
Mediators of inflammation

- Bradykinin
- ATP
- Prostaglandin
- 5-HT
- Histamine
- H⁺
- Substance P
- CGRP
- Dorsal root ganglion cell body
- Spinal cord
- Mast cell or neutrophil
- Anterolateral system
The somatosensory thalamus
Somatosensory thalamus topography

Somatotopy (VPL)
Thalamus

thalamic nuclei can be categorized on their location within the thalamus or according to function
Corticothalamic afferents terminate in:
• Layer 4 but some 3 and 5
• Layer 6
• Layer 1 and sometimes 2
Cortical regions involved in pain perception
Affective and Discriminative aspects of pain

- Localization and Intensity
  - Primary somatosensory Cortex

- Affective Component
  - Cingulate Cortex
  - Insular cortex
Expectance can alter pain

Pain (expect pain)

Warm (expect pain)

Warm (expect warm)

Sawamoto et al. 2000
Referred pain

Pain interpreted as originating in distribution of somatic sensory nerves.
Motor systems

Cerebrum, cerebellum, brainstem, and spinal cord

Central nervous system

SENSORY COMPONENTS
- Sensory ganglia and nerves
- Sensory receptors

MOTOR COMPONENTS
- VISCERAL MOTOR SYSTEM
  - Autonomic ganglia and nerves
- SOMATIC MOTOR SYSTEM
  - Motor nerves

PERIPHERAL nervous system

INTERNAL AND EXTERNAL ENVIRONMENT

EFFECTORS
- Smooth muscles, cardiac muscles, and glands
- Skeletal muscles
Descending pathways

- Vestibular nucleus
- Reticular formation
- Red nucleus
- Superior colliculus
Descending Projections from the Brainstem

Vestibular nucleus – maintenance of posture
Reticular formation – integration of muscle groups
Superior colliculus – movement of head and neck with visual input.

Red nucleus – similar function to motor cortex
The motor tracts in the spinal white matter

- Gracilis fasciculus
- Cuneanus fasciculus
- Dorsal spinocerebellar tract
- Lateral corticospinal tract
- Rubrospinal tract
- Lateral reticulospinal tract
- Medial reticulospinal tract
- Vestibulospinal tract
- Anterolateral system
- Ventral corticospinal tract
- Medial tectospinal tract
- Lateral tectospinal tract
Basal ganglia: Anatomy
Basal Ganglia connections

**Input**
- Cerebrum
- Frontal cortex
- Parietal cortex
- Temporal cortex
- Midbrain

**Output**
- Motor cortex
- Caudate
- Putamen
- Internal capsule
- Globus pallidus, external segment
- Globus pallidus, internal segment
- Substantia nigra pars compacta
- VA/VL thalamic nuclei
- Subthalamus
- Superior colliculus
- Substantia nigra pars reticulata
Direct and Indirect pathway

(B) Indirect and direct pathways

Indirect pathway

Substantia nigra pars compacta

<table>
<thead>
<tr>
<th>D1</th>
<th>+</th>
</tr>
</thead>
<tbody>
<tr>
<td>D2</td>
<td>-</td>
</tr>
</tbody>
</table>

GABA/ENK → Caudate/putamen

GABA/SP → Globus pallidus, external segment

GABA/ENK → Subthalamic nucleus

Association cortex

| Glu | + |

Motor cortex

| Glu | + |

VA/VL complex of thalamus

| GABA | - |

Parkinson’s: basal ganglia circuitry

(B) Indirect and direct pathways

(A) Parkinson’s disease

Indirect pathway

Substantia nigra pars compacta

Caudate/putamen

Globus pallidus, external segment

Globus pallidus, internal segment

Subthalamic nucleus

Motor cortex

VA/ VL complex of thalamus

Neocortex

VA/ VL complex of thalamus

Motor cortex

More tonic inhibition

Relationship of Cerebellum to descending motor pathways

- Cerebrum, cerebellum, brainstem, and spinal cord
- Sensory components
  - Sensory ganglia and nerves
  - Sensory receptors
- Motor components
  - Visceral motor system (autonomic ganglia and nerves)
  - Somatic motor system (motor nerves)
- Effectors
  - Smooth muscles, cardiac muscles, and glands
  - Skeletal muscles
- Internal and external environment

Descending systems

Upper Motor Neurons
- Motor Cortex
  - Planning, initiating, and directing voluntary movements
- Brainstem Centers
  - Basic movements and postural control
- Basal ganglia
  - Gating proper initiation of movement
- Cerebellum
  - Sensory motor coordination

Local circuit neurons
- Reflex coordination

Motor neuron pools
- Lower Motor Neurons

Spinal cord and brainstem circuits

Skeletal muscles
Cerebellum
The Cerebellum: Connections

**Input**
- Motor cortex
- Parietal cortex
- Pontine nuclei
- Vestibular nuclei
- Dorsal nucleus of Clarke
- Spinal cord

**Output**
- Primary motor and premotor cortex
- Ventral lateral complex (thalamus)
- Pontine nuclei
- Vestibular nuclei
- Inferior olive
- Dorsal nucleus of Clarke
- Deep cerebellar nuclei
- Cerebellar cortex

Graphical representation showing the connections between the cerebellum and other brain regions.
Cerebellum: Connections

**Input**

- Frontal-motor/parietal cortex
- Pons
- Middle cerebellar peduncle
- Cerebellar cortex
  - Inferior olive
  - Spinal cord
  - Vestibular nucleus
- Mossy fibers
- Climbing fibers

**Output**

- Primary motor and premotor cortex
- VL complex (thalamus)
- Cerebellar cortex
- Deep cerebellar nuclei
- Superior cerebellar peduncle
Stretch reflex

α Motor neuron
Ia afferent
Muscle spindle
Homonymous muscle
Synergist
Antagonist
Spinal reflexes

- Spindle afferents
- Segmental connections
- Interneurons (excitatory and inhibitory)
- Corticospinal tract
- Rubrospinal tract
- Tectospinal tract
- Vestibulospinal tract
An **upper motor neuron lesion (cortical lesion)** Causes **paralysis**,  
Reflexes becomes **spastic** (muscle tone increases),  
The muscle does not **atrophy**.  
If the sole of the foot is stroked, the toe dorsiflexes.  
This is the **Babinski response**.

A **lower motor neuron lesion**  
All excitation of the muscle is lost  
the muscle becomes **paralyzed** (unable to move)  
**flaccid** (muscle tone decreases).  
the muscle will eventually **atrophy**.
Lesions of the basal ganglia generally lead to hyper- or hypo-kinetic movement and resting tremors.

Lesions of the cerebellum lead to errors in accuracy and coordination of movements and intention tremors.
A 68 year old woman with hypertension and diabetes develops abrupt onset numbness and tingling on the right half of the face and head and the entire right hemitrunk, right arm and right leg. She does not experience any weakness or incoordination.

**Physical Examination:**
Vitals: T 37.0° C; BP 168/87; P 86; RR 16
Cardiovascular, pulmonary, and abdominal exam are within normal limits.

**Neurological Examination:**
**Mental Status:** Alert and oriented x 3, 3/3 recall in 3 minutes, language fluent.
**Cranial nerves:** CN II-XII intact except for objective loss of all sensation (including fine touch, two point discrimination, pain and temperature) on the right side of the face.
**Motor:** Normal bulk and tone. Strength and reflexes are as follows:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>5/5</td>
<td>5/5</td>
<td>5/5</td>
<td>5/5</td>
<td>5/5</td>
<td>5/5</td>
<td>5/5</td>
</tr>
<tr>
<td>L</td>
<td>5/5</td>
<td>5/5</td>
<td>5/5</td>
<td>5/5</td>
<td>5/5</td>
<td>5/5</td>
<td>5/5</td>
</tr>
</tbody>
</table>

**Sensation:** Intact fine touch, two point discrimination, vibration, joint position sense, pain and temperature sensation in the left arm, left leg and left hemitrunk. Complete sensory loss of all modalities in the right arm, right hemitrunk and right leg.

**Coordination:** Normal rapid alternating movements in the upper and lower extremities, and normal finger-to-nose and heel-knee-shin testing.

**Gait:** Normal

Where is the most likely location of the lesion that gives rise to these symptoms?
As a volunteer working for Doctors Without Borders in a clinic in Jordan, you are asked to evaluate a 14 year-old Iraqi refugee who was injured by a sniper’s bullet 7 weeks ago. The bullet entry hole is obliterated by an apparent attempt at exploratory surgery in the mid-back, and plain x-rays show that the bullet was lodged somewhere in the bony spine.

**Physical Examination:**
Vitals: T 37.6° C; BP 112/60; P 64; RR 12
Cardiovascular and abdominal exam are within normal limits. Pulmonary exam reveals mild crackles in the upper right lung field.

**Neurological Examination:**
**Mental Status:** AO x 3, 3/3 recall in 3 minutes, language fluent.
**Cranial nerves:** CN II-XII intact.
**Motor:** Normal bulk. Increased tone (spasticity) in the left lower extremity. No pronator drift.
**Sensation:** Markedly decreased pain and temperature sensation on the right side only from the level of the umbilicus down to and including the entire right leg. Vibration and joint position sense normal bilaterally in the upper and lower extremities.
**Coordination:** Normal rapid alternating movements and finger-to-nose in the upper extremities. Slow foot tap in the left leg.
**Gait:** Spastic with impaired movement of the left leg (circumduction of the left leg during swing-through phase of gait).

*Q – Diagram a single continuous lesion that can explain these findings.*