Pain Pathophysiology Unraveled

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Disclosures

- Nothing to disclose
Learning Objectives

- Differentiate between nociceptive and neuropathic pain
- Describe the process of pain transmission
- Identify the specific pain pathways that can be acted upon by common pharmacotherapy classes

Classification of Pain

- Good pain vs bad pain
**Good Pain**

- **Nociceptive pain**: purposeful pain
  - **Eudynia**: being in pain linked to normal tissue function or damage
  - Non-maldynic pain
  - Adaptive

**Bad Pain**

- **Neuropathic pain**: non-purposeful pain
  - **Maldynia**: pain linked to disorder, illness, or damage
  - i.e. may be abnormal, unfamiliar pain, assumed to be caused by dysfunction in PNS or CNS
Pain Mechanisms


General Anatomy of Pain

Cortex and subcortical regions: Perception, sensory, & affective pain components

Brainstem: Descending modulation

Spinal cord: Synaptic transmission, modulation & central sensitization

Periphery: Transmission & peripheral sensitization

Pain Roadmap:
Peripheral and Central Nervous System Landmarks

- Physiologic process involving multiple areas of the nervous system
- Bidirectional
- Involves normal as well as pathological processes
- A sensory experience associated with affective and cognitive responses
- Dynamic (i.e. occurring in real time)
- Adapts or changes in response to function—“neuroplasticity”

Common Types of Pain

Nociceptive pain
- Noxious stimuli
  - Heat
  - Cold
  - Mechanical force
  - Chemical irritants
- Adaptive, high-threshold pain
  - Early warning system (protective)

Inflammatory pain
- Macrophage
- Mast cell
- Neutrophil
- Granulocyte
- Tissue damage
- Adaptive, low-threshold pain
  - Promotes repair (protective)

Neuropathic pain
- Neural lesion
  - Positive and negative symptoms
- Peripheral nerve damage
  - Maladaptive, low-threshold pain
  - Disease state of nervous system

Functional pain
- Non-Neuropathic
- Non-Inflammatory
  - Dysfunctional pain
  - Normal peripheral tissue and nerves
  - Maladaptive, low-threshold pain
  - Disease state of nervous system

Nociceptive vs Neuropathic Pain


Perception
Cortex and subcortical regions: sensory, and affective pain components
- Behavioral/Limbic

Transduction
Peripheral nociceptor converts input to electric charge

Transmission
Spinal Cord/Ascending Spinal Pathways

Conduction
Peripheral nerve synapsing in the dorsal horn

PAG = periaqueductal grey
RVM = rostral ventromedial medulla

Pain Pathway Steps

Adapted from Schultz J, Woolf CJ. Nat Neuroscience, 2002;5:1062-1067
Molecular Elements: Peripheral—Central

**Transduction**
TRPV1, TRPV2, TRPV3, TRPMB
ASIC, DRASIC
MDEG, TREK-1
BK1, BK2
P2X3

Membrane excitability of peripheral afferents
Na1.8, Na1.9
K+ channel

Peripheral sensitization
NGF, TrkA
TRPV1
Na1.8
PKA, PKC isoforms, CaMK IV
Erk ½, p38, JNK
IL-1b, cPLA2, COX2, EP1, EP3, EP4

**Central Inhibition**
GABA, GABA_A-R, GABA_B-R
Glycine-R
NE, 5-HT
Opioid receptors
CB1

**Synaptic Transmission**
Presynaptic
VGCC
Adenosine-R
(mGlu-R)

Postsynaptic
AMPA/kainite-R, NMDA-R, mGlu-R
NK1
Na1.3
K+ channel

**Signal transduction**
PKA, PKC isoforms
ERK, p38, JNK

**Gene expression**
c-fos, c-jun, CREB, DREAM

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Transduction: Processing at Peripheral Nerve Endings

- Conversion of mechanical, thermal or chemical stimuli into an electric charge
- Involves
  - Receptors activated directly by stimuli
  - Injury/inflammatory response

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Adapted from Scholz J, Woolf CJ, Nature Neuroscience supplement Vol 5, 2002

How is Pain Transduced?

- Nociception
  - Mechanical
  - Thermal
  - Chemical

- Mediators
  - Prostaglandins
  - Leukotrienes
  - Substance P
  - Histamine
  - Bradykinin
  - Serotonin
  - Hydroxyacids
  - Reactive oxygen species
  - Inflammatory cytokines and chemokines

Conduction

- Conduction impulses from primary nociceptors to the spinal cord (dorsal horn) along the peripheral nerve
Primary Nociception

- A-delta fibers
  - Small receptive fields
  - Thermal & mechanical
  - Myelinated
  - Rapidly conducting
    • 10-30 m/sec
  - Large diameter

- C-fibers
  - Broad receptive fields
  - Polymodal
  - Unmyelinated
  - Slower conducting
    • .5-2.0 m/sec
  - Cross sensitized
  - Small diameter

Peripheral Pain Nociceptors

Aβ - muscle spindle secondary endings, touch, and kinesthesia.
Aδ - pain, temperature, crude touch, and pressure.

Transmission & Modulation

Ascending nociceptive pathways
Transmitting nociceptive impulses from the dorsal horn to surraspinal targets
- **Fast** (green) Neospinalthalamic
- **Slow** (yellow) Paleospinalthalamic

Descending inhibitory tracts
- (blue)
  - Increase or decrease volume control of incoming nociceptive signals reaching the brain
  - 5-HT - Serotonin
  - NE - Norepineherine

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How is Pain Conducted and Transmitted?

- **Excitatory Transmitters**
  - Substance P
  - Calcitonin gene related peptide
  - Aspartate, Glutamate

- **Inhibitory Transmitters** (descending inhibitory pathways)
  - GABA
  - Glycine
  - Somatostatin
  - a2 agonists
Role of Neuronal Plasticity in Pain

- Nervous system changes in
  - Neuronal structure
  - Connections between neurons
  - Quantity/properties of neurotransmitters, receptors, ion channels
- Decreases body’s pain inhibitory systems (increased pain)
- Injury, inflammation, and disease are culprits
- Produces short-term and permanent changes
- Pivotal to the development of hypersensitivity of inflammatory pain

- Enables NS to modify its function according to different conditions or demands placed upon it

How Acute Pain Becomes Chronic

- Peripheral sensitization
  - Tissue damage releases sensitizing “soup” of cytokines and neurotransmitters
  - COX-mediated PGE2 release
  - Sensitized nociceptors exhibiting a decreased threshold for activation and increased rate of firing

- Central sensitization—Resulting from noxious input to the spinal cord
  - Resulting in hyperalgesia and allodynia
Definitions

- **Hyperalgesia**
  - Lowered threshold to different types of noxious stimuli

- **Allodynia**
  - Painful response to what should normally be non-painful stimuli

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Neuroplasticity in Pain Processing

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Neuroplasticity in Peripheral Pain Transmission

Peripheral Sensitization
How Acute Pain Becomes Chronic

- Central sensitization
  - Activation
    • “Wind up” of dorsal horn nociceptors
  - Modulation
    • Excitatory/Inhibitory neurotransmitters
  - Decreased central inhibition of pain transmission
  - Prime role in chronic pain, particularly neuropathic pain

Definitions

- Wind Up
  - Causes long-term changes in nociceptive neurons, which become hyperexcitable such that they respond to lower stimuli
    - NMDA-type glutamate receptors play an important role in this process\(^1,2,3,4\)
    - Prolonged opening of the ion channels enables greater influx of calcium and sodium across the post-synaptic membrane and greater excitation of nociceptive neurons\(^2,3\)

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Central Sensitization

Afferent first order neuron

Dorsal horn neuron

NK-1 = Neurokinin 1 receptor; AMPA = alpha-amino-3-hydroxy-5-methyl-4-isoxazolepropionic acid; NMDA = N-methyl-D-aspartic acid; VGCC = voltage gated sodium channel; TrkB = tropomyosin receptor kinase B; BDNF = Brain derived neurotrophic factor; SP = substance P

Adapted from Schlotz J, Woolf CJ. Nat Neuroscience. 2002;5:1062-1067

Central Sensitization (cont’d)

Key Influences upon signal propagation

- Excitatory neurotransmitters
  - Substance P, CGRP, glutamate
- NMDA channel activity
  - Glutamate binding
  - Altering channel activity
- Descending inhibitory tracts
  - NE/serotonin (5HT)
- Mu opioid receptor

Adapted from Schlotz J, Woolf CJ. Nat Neuroscience. 2002;5:1062-1067
Dorsal Horn of the Spinal Cord Serves as a Relay Station in Pain Processing\textsuperscript{1,2}

Spinal cord glial cell

A\textdelta

C Fiber

Descending inhibitory axon

Second-order projection neuron (to brain)

GABA-ergic inhibitory interneuron


Neuroplasticity: Neural Reorganization

Photo courtesy of Professor S.B. McMahon

CTB = cholera toxin B
Neuroplasticity: Cross Talk

Central Sensitization:
Neuroplasticity in Spinal Cord Processing

- Definition: Altered function of neurons or synaptic activity
- Mechanisms of central sensitization may include:
  - Changes effecting glutamate/NMDA receptors activity
    - Reduced threshold for activation
    - Increased availability of glutamate
    - Increased influx of Na⁺/Ca⁺ (receptor open longer)
  - Modulation—excitatory/Inhibitory neurotransmitters
  - Decreased tone—descending inhibitory pathways²
  - Activation/migration of glial cells into the spinal cord³
  - Changes in the thalamus and primary somatosensory cortex⁴

Brain Regions Involved in Pain Processing

- Somatosensory cortex: Localization
- Thalamus: Routing
- Hippocampus: Pain memory/Learning
- Amygdala: Emotional Aspect
- Prefrontal cortex: Motor planning
- Anterior cingulate cortex: Context/situation of pain
- Insular cortex: Pain judged to the degree and where pain is imagined

Analgesics That Modify Pain Processes

- **Transduction**
  - NSAIDs
  - Antihistamines
  - Membrane stabilizing agents
  - Local anesthetic cream
  - Opioids
  - Bradykinin & Serotonin antagonists

- **Perception**
  - Parenteral opioids
  - $\alpha_2$ agonists
  - General anesthetics

- **Transmission/Modulation**
  - Spinal opioids
  - $\alpha_2$ agonists
  - NMDA receptor antagonists
  - NSAIDs
  - NO inhibitors
  - K+ channel openers

- **Conduction**
  - Local anesthetics
    - Peripheral nerve, plexus, epidural block
Pharmacological Targets in Pain

Ectopic Activity
- Non-inherited Mutations
- Pain’s channel blockers
- M1/M6 receptor antagonists
- Antigen-specific inhibition

Descending Modulation
- Cerebral 3-arrestins
- Catecholamines
- Dopaminergic/transmitter

Peripheral Sensitization
- NSAIDs
- Venlafaxine

Central Sensitization
- Peripheral inflammation
- Central sensitization
- Neuropathic pain
- Anticonvulsants

The Chronic Pain Armamentarium

**Nonopioids**
- Acetaminophen
- NSAIDs
- COX-2 inhibitors

**Opioids**
- Mu-opioid agonists
- Mixed agonist-antagonists

**Adjuvant analgesics**
- Antidepressants
- Anticonvulsants
- Topical agents/local anesthetics
VA DoD Stepped Pain Care Model

Common Pharmacologic Therapies

- Acetaminophen
- NSAIDS
- Antiepileptics
- TCAs
- SNRIs
- Topicals
- Muscle relaxants
- Opioids
**Nonopioids: Acetaminophen**

*Example*
- Acetaminophen

*Mechanism of action*
- Inhibits prostaglandin production in CNS; antipyretic activity
- No effect on blocking peripheral prostaglandin production; no anti-inflammatory or antirheumatic activity

*FDA Warning*
- Potential severe liver damage if over-used
- Stevens-Johnson Syndrome and toxic epidermal necrolysis

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**Nonopioids: NSAIDs**

*Examples*
- Acetylated (aspirin); nonacetylated (diflunisal); acetic acid (diclofenac); propionic acid (naproxen); fenamic acid (mefenamic acid); enolic acids (piroxicam); nonacidic (nabumetone); ibuprofen, selective COX-2s (celecoxib)

*Mechanism of action*
- Exhibit both peripheral and central effects; antiinflammatory and analgesic effects
- Inhibition of cyclooxygenase and prostaglandin production
- Inhibition of leukotriene B4 production
- Lipoxins (signaling resolution of inflammation)
Opioids

**Examples**
- Morphine, hydromorphone, fentanyl, oxycodone, oxymorphone, meperidine, codeine, methadone, tramadol

**Mechanism of action**
- Bind to opioid receptors in the central nervous system (CNS) to inhibit transmission of nociceptive input from periphery to spinal cord
- Activate descending pathways that modulate transmission in spinal cord
- Alter limbic system activity; modify sensory and affective pain aspects
Modulation of Central Sensitization by 5-HT & NE Descending Pathways

Mechanism of Action: Opioids

Adapted from Woolf C, Max M. Anesthesiology 2001
Adjuvant Analgesics: Tricyclic Antidepressants

**Examples**
- Amitriptyline, desipramine, doxepin, imipramine, nortriptyline

**Mechanism of action**
- Reduction in action potential firing of sodium channel activity
- Inhibition of reuptake of NE and 5-HT
- Analgesia is independent of antidepressant function
- High side effect profile (tolerability)
  - cardiotoxic (overdose)

TCAs and SNRIs Pharmacological Properties

http://pharmacologycorner.com
SSRIs  (Selective Serotonin Reuptake Inhibitors)

Examples
– Citalopram, fluoxetine, fluvoxamine, paroxetine, and sertraline

Mechanism of action
– Selectively inhibit 5-HT reuptake without affecting NE

Therefore, no pain relief expected!

Serotonin

- International Union of Pure and Applied Chemistry nomenclature
  – 5-Hydroxytryptamine (5-HT)
  – Monoamine neurotransmitter, biochemically derived from tryptophan
  – Receptors are a group of G protein-coupled receptors (GPCRs) and
    ligand-gated ion channels (LGICs) found in the central and peripheral
    nervous systems
Serotonin/5-HT Receptors

- 5-HT1a (Blood Ves/CNS)
  - Addiction
  - Aggression
  - Anxiety
  - Appetite
  - BP
  - Cardiovascular function
  - Emesis
  - Heart rate
  - Impulsivity
  - Memory
  - Mood
  - Nausea
  - Nociception
  - Penile erection
  - Pupil dilatation

- 5-HT1a (cont)
  - Respiration
  - Sexual behavior
  - Sleep
  - Sociability
  - Thermoregulation

- 5-HT5a & 5-HT6 (CNS)
  - Locomotion
  - Sleep
  - Anxiety
  - Cognition
  - Learning
  - Memory
  - Mood
**SNRI**s (Serotonin/Noradrenaline Reuptake Inhibitors)

*Examples*
- Duloxetine, milnacipran, and venlafaxine

*Mechanism of action*
- Block reuptake of 5-HT and NA
  - Better tolerated, lower tendency for drug-drug interactions, better overdose safety

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**Modulation of Central Sensitization by 5-HT & NE Descending Pathways**
Site of Action: SNRIs

Adapted from Woolf C, Max M Anesthesiology 2001

Adjuvant Analgesics: Antiepileptics

Examples
- Gabapentin, pregabalin*, carbamazepine, phenytoin, divalproex sodium, clonazepam, levetiracetam, topiramate, lamotrigine

Mechanism of action
- Suppress neuronal hyperexcitability via
  - Reducing neuronal influx of sodium (Na+) and calcium (Ca+ +)
  - Direct/indirect enhancement of GABA inhibitory effects
  - Reduce activity of glutamate and/or blocking NMDA receptors
  - Binds the α2δ subunit of voltage gated Ca+ channels, inhibit NT release
Site of Action: Antiepileptics

Adjuvant Analgesics: Topicals

**Examples**
- Lidocaine patch 5%, eutectic, mixture of lidocaine and prilocaine
- Capsaicin cream/patch
- Diclofenac (cream/liquid/gel/patch)

**Mechanism of action**
- Block sodium channels and inhibit generation of abnormal impulses by damaged nerves
- Depletion of peripheral small fibers and therefore Substance P release from sensory nerve endings
- Target local inflammatory response
**Muscle Relaxants**

- Decrease tone of skeletal muscles
- Subclasses
  - Neuromuscular blockers
    - Act at the neuromuscular junction
    - Often used in surgery to cause temporary paralysis
  - Spasmolytics
    - Centrally acting

**Muscle Relaxants: Spasmolytics**

- Enhancing the level of inhibition
  - Mimicking or enhancing the actions of endogenous inhibitory substances, such as GABA
- Reducing the level of excitation
- Common examples
  - Cyclobenzaprine (TCA) methocarbamol, carisoprodol, tizanadine (α-2 agonist), baclofen (GABA agonist), orphenadrine (benzodiazepine)
- Common adverse effects
  - Sedation, lethargy & confusion (cyclobenzaprine), dependence (carisopradol)
Case Study

- 54-year-old with 3 year history of neck, shoulder, and upper extremity pain following a lifting injury
  - Current medications
    - Fluoxetine
    - Milnacipran
    - Gabapentin
    - Clonazepam
    - Alprazolam
    - Robaxin
    - Tapentadol
    - Acetaminophen and propoxyphene
    - Zolpidem
    - Diclofenac topical
    - Acetaminophen

Importance for Understanding Pain Mechanisms

- Allow for rational rather than empirical approach to pain control
- Foster the development of diagnostic tools to identify specific pain mechanisms
- Facilitate pharmacotherapies that act on specific pain pathways and mechanisms
- Reduce the number of pharmacotherapies and incidence of drug-related adverse events (rationale polypharmacy)
- Enhances use of non-pharmacologic treatments
- Improve overall patient care and outcome
  - Tailoring treatment based on the individual patient and pain type
- Do not forget to look for the spear