



Spinal Biomechanics and Instrumentation

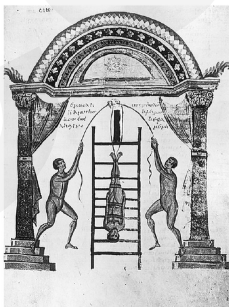
Prof M J H McCarthy
Consultant Spinal Surgeon

Plan

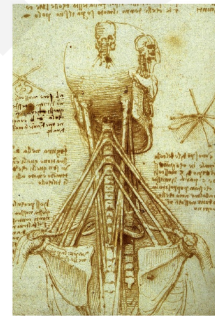
- Recap Biomechanics
- Spine Structure and Function
- Spinal Instrumentation



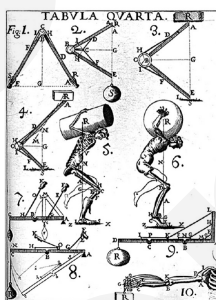
Hippocratic Ladder



Da Vinci c1500



Borelli c1650



Newton's Laws

1. Inertia
 - a body is at rest or moving at a constant speed in a straight line, it will remain at rest or keep moving in a straight line at constant speed unless it is acted upon by a force
 2. Acceleration
 - the time rate of change of the momentum of a body is equal in both magnitude and direction to the force imposed on it
 3. Reactions
 - when two bodies interact, they apply forces to one another that are equal in magnitude and opposite in direction
- Force = the action causing acceleration of a mass in a certain direction



Loading / Forces

- Tensile - pull
- Compressive - push
- Shear - twist
- Biaxial
- Hydrostatic
- Bending
- Torsion



Definitions

- Moment
 - Rotational effect of force acting at a distance from a specified point on a body
- Work
 - Force x displacement
- Energy
 - Ability to perform work (potential and kinetic)
- Friction
 - Resistance to motion of two bodies when one slides over the other



Definitions

Pressure = external

- Stress
 - Intensity of internal force
 - Internal resistance of a body to load
- Strain
 - Measure of deformation of a body as a result of loading
 - Change in unit length / angle
- Modulus Elasticity (Youngs)
 - Ratio of normal stress to normal strain in a material
 - Measure of stiffness of a material or its ability to resist deformation in tension
- Elastic
 - Property of material to return to original form after removal load
- Plastic
 - Property of material to permanently deform when it is loaded beyond its elastic range

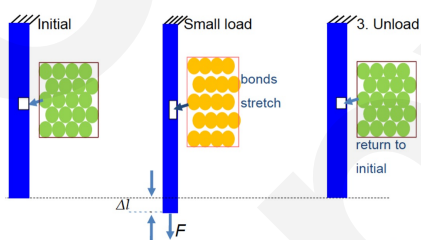


Definitions

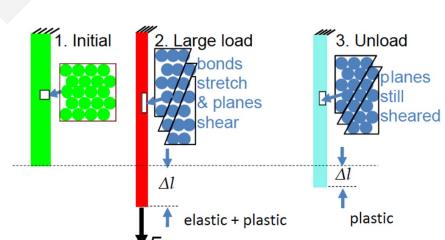
- Stiffness
 - Describes elastic deformation of a material
 - Stiff material resists deformation - sometimes referred to as rigid
 - Depends on stiffness of bonds, number of bonds, orientation / interconnection of bonds
- Structural Rigidity
 - Describes the resistance of a structure to deformation (not a material)
- Structure takes into account material and shape
- Shear
 - Force applied so as to cause or tend to cause 2 adjacent parts of the same body (material) to slide relative to each other in a direction parallel to their plane of contact
- Shear Stress
 - Intensity of force parallel to the surface on which it acts



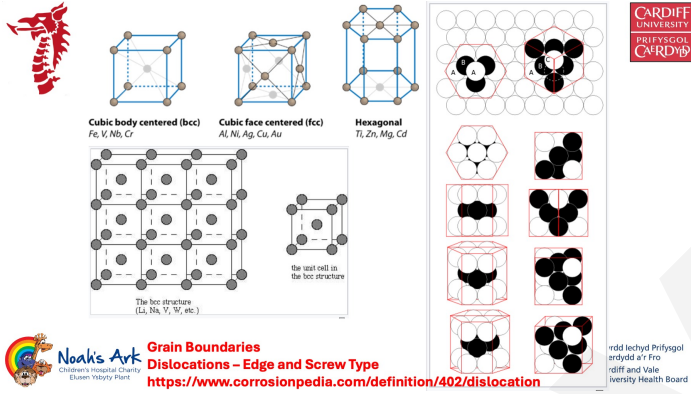
Elastic Deformation



Plastic Deformation



Plastic means permanent or non-recoverable!

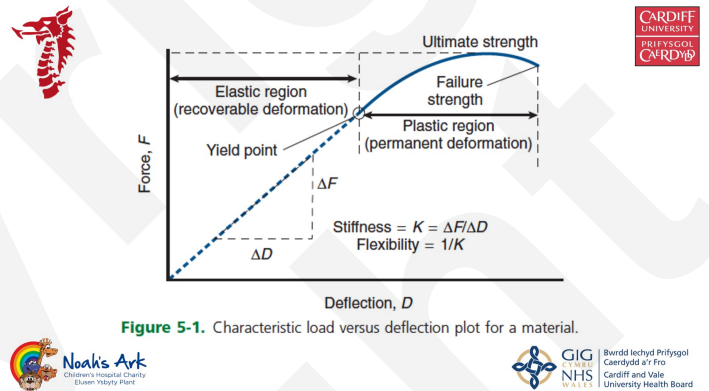


Definitions

- **Viscoelastic**
 - Time rate dependent stress strain behavior
 - Material deformation depends on the load and rate at which it is applied
- **Creep**
 - Time dependent deformation under constant load
- **Ductile**
 - Material that can undergo large amount of plastic deformation prior to failure
- **Brittle**
 - Material that has little or no capacity to undergo plastic deformation prior to failure

Definitions

- **Strength**
 - Force required to break something
 - Depends on the plastic deformation properties
- **Toughness**
 - Energy required to break something
 - Opposite is brittle
- **Hardness**
 - Resistance to indentation – surface property
- **Fatigue**
 - Process of birth and growth of cracks in structures subject to repetitive load (below failure load)

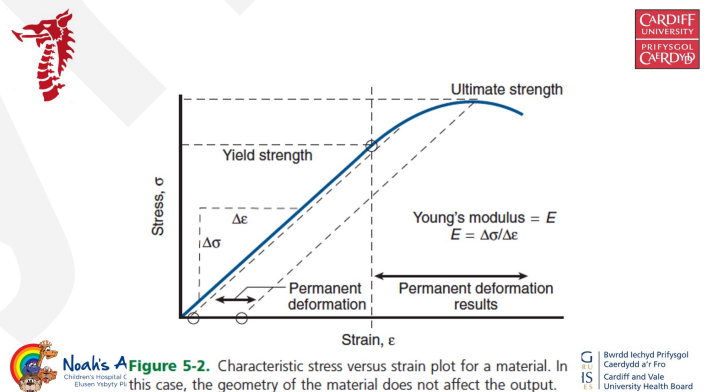


Stress: $\sigma = \frac{F}{A_0}$ (N/m² or Pa)

Strain: $\epsilon = \frac{\Delta l}{l_0} = \frac{l - l_0}{l_0}$ (no unit or mm/mm); $\Delta l = l - l_0$ is extension

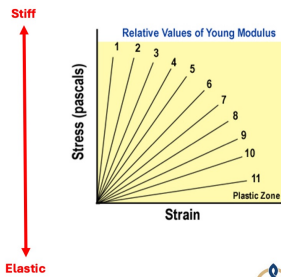
Elastic Modulus $E = \frac{\sigma}{\epsilon}$ (N/m² or Pa)

• E is also known as Young's modulus.



Materials Stress Strain

1. Ceramic (Al₂O₃)
2. Alloy (CoCrMo)
3. Stainless Steel
4. Titanium
5. Cortical Bone
6. Matric polymers
7. PMMA
8. Polyethylene
9. Cancellous Bone
10. Tendon / Ligament
11. Cartilage



Viscoelastic Curve

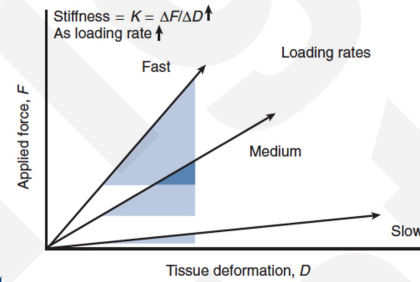


Figure 5-3. Effects of loading on viscoelastic materials.

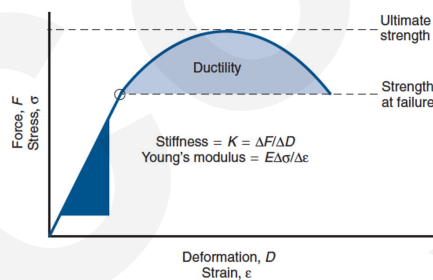
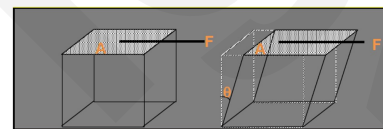


Figure 5-4. An implant can be stiff, strong, and ductile simultaneously.



$$\text{Shear Stress } (\tau) = \frac{\text{Shear Force}}{\text{Area}} \quad \text{N/m}^2$$

$$\text{Shear Strain } (\gamma) = \tan \theta \approx \theta \quad (\text{small } \theta)$$

$$G = \text{shear modulus} = \frac{\tau}{\gamma} \quad \text{N/m}^2$$

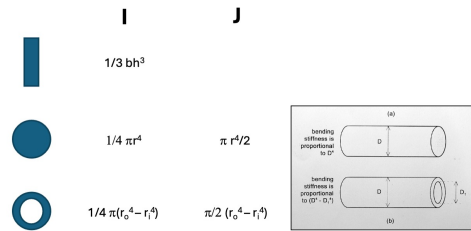
Bending and Torsional Rigidity

- Bending rigidity of a structure related to area moment of inertia (I)
- Torsional rigidity of a structure related to polar moment of inertia (J)
- Functions of distribution of material in a cross section of the structure

Bending and Torsional Rigidity

- Bending rigidity
- $\sigma = My / I$
- Stress = resultant moment x distance for neutral axis / area moment inertia
- Torsional rigidity
- $\tau = Tr / J$
- Shear stress = torque x radius / polar moment inertia

Bending and Torsional Rigidity



For the same volume of material, cannulated rod is stiffer / structural rigidity

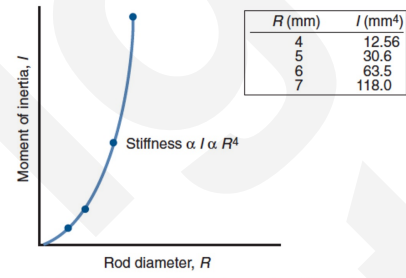


Figure 5-5. The moment of inertia for a rod and hence its strength is proportional to the fourth power of the radius.

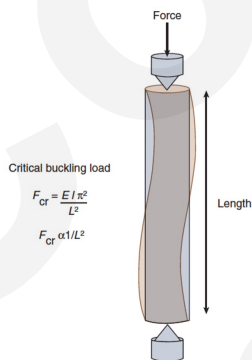
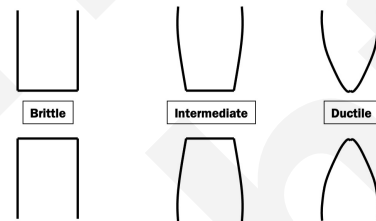
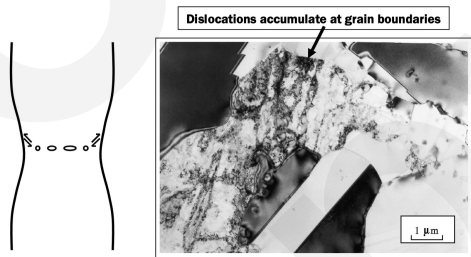


Figure 5-6. The buckling theory of a long, slender column.

Fracture

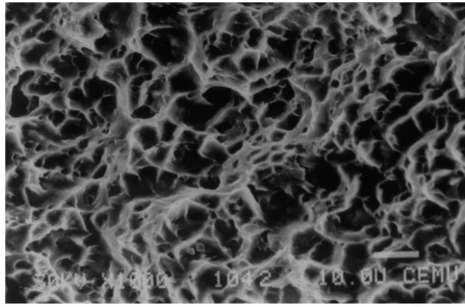


Ductile Fracture

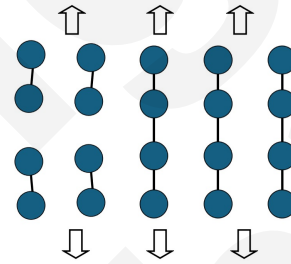


Ductile Fracture

- Most metals eventually fail by ductile fracture
- Microvoids form at the grain boundaries due to slip
 - Dislocations / slip are linear crystalline defects around which there is atomic misalignment
 - Edge / Screw / Mixed types
- Voids coalesce to form a crack – necking and elongation
- Edges fail by shear
- On a small scale, a lot of plastic deformation usually takes place and the fracture surface has very pronounced dimples.
- Shear failure produces lips at 45° and elongated dimples on the fracture surface.



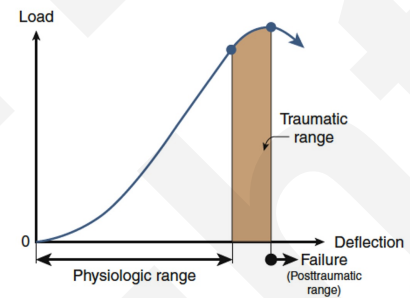
Brittle Fracture



Brittle fracture

- Common in ceramics and also in some metals such as cast iron and some types of steel
- A crack runs through the lattice (or along the grain boundaries), breaking one bond at a time
- The fracture surface is smooth and glassy in appearance for transgranular fracture (ceramics) or granular for intergranular fracture (some metals - characteristic chevron markings are often found in steels)

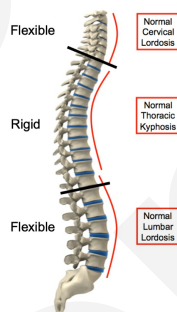
Biomechanics Relative to Body



Spinal Biomechanics

- Anterior Column
 - 80% Load
 - Compression
- Posterior Column
 - 20% Load
 - Tension

- Function of Spine
 - Movement
 - Protect
 - Support



Spinal Biomechanics Bone

- Provides load-bearing function of the spine
 - Vertebral size increases down the spinal column
- Subjected mainly compressive loads
- Trabecular core carries ~55% of total loading
 - This decreases with age (& osteoporosis) to ~35%
- Trabeculae orientation vertical and transverse
 - Most effective orientation to resist compressive loading
- Facet joints 0-33% of total loading
- Facet joint orientation limits adjacent movement

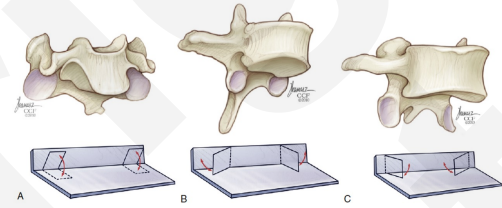


Spinal Kinematics

- Motion segments
- Flexibility
 - Large overall flexibility is achieved by small displacements at each motion segment
 - Limits both disc compression and ligament stretch
- Control of motion
 - By muscular action
 - By facet joint orientation



Facet Orientation

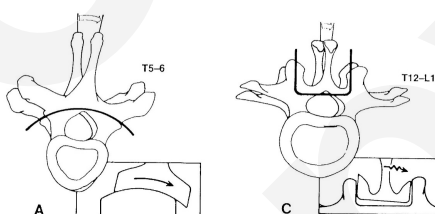


Movements Allowed in the Craniocervical Region		
Joint	Motion	Range of Motion (degrees)
Occiput-C1	Combined flexion/extension	25
	Lateral bending (unilateral)	5
	Axial rotation (unilateral)	5
C1-2	Combined flexion/extension	20
	Lateral bending (unilateral)	5
	Axial rotation (unilateral)	40

Normal Motion of the Cervical Spine		
	Maiman et al.*	Johnson et al.†
Lateral bending	64.2 (± 6.8)	
Rotation	134.2 (± 17.1)	
Flexion-extension		
OC-C1	16.7 (± 10.0)	13.6 (± 6.0)
C1-2	11.6 (± 4.7)	15.2 (± 3.8)
C2-3	17.1 (± 4.5)	17.1 (± 3.9)
C3-4	18.1 (± 6.1)	18.8 (± 2.2)
C4-5	13.7 (± 1.7)	12.0 (± 1.2)
C5-6	17.6 (± 1.5)	20.1 (± 1.6)
C6-7	21.8 (± 1.6)	20.7 (± 1.6)



Facet Movement



Spinal Kinematics

	Flexion-extension	Lateral bending	Axial rotation
Cervical	✓✓✓✓	✓✓	✓✓✓
Thoracic	✓✓	✓	✓✓
Lumbar	✓✓✓✓	✓✓	✓



✓ = ~ 5° of movement



Anatomy Spinal Muscles

- Act to stabilise the spine
- Provide movement
- May act to limit injury during non-physiological loading



Muscles of the Back

- Superficial
 - Iliocostalis, longissimus, spinalis
 - Aka ERECTOR SPINAE
- Intermediate
 - Semispinalis (capitis, cervicis, thoracis), levator costarum, **multifidus**
 - Aka TRANSVERSOSPINALES
- Deep
 - Interspinalis, intertransversalis, rotatores
- Supplied posterior primary rami



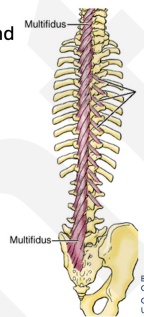
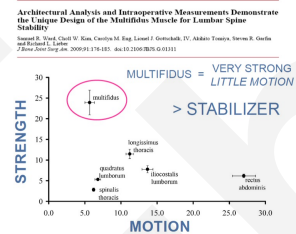
Muscles of the Back

- Covering Muscles
 - Splenius capitis
 - Serratus posterior superior
 - Rhomboid minor
 - Rhomboid major
 - Serratus posterior inferior
 - Trapezius
 - (laterally – latissimus dorsi and serratus anterior)
 - (anteriorly – psoas, quadratus lumborum, abdominal muscles)



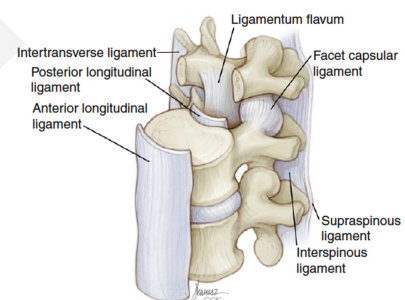
Multifidus

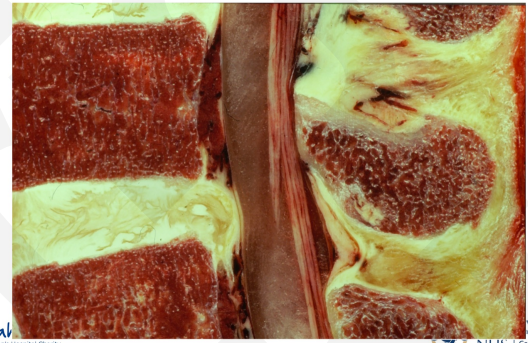
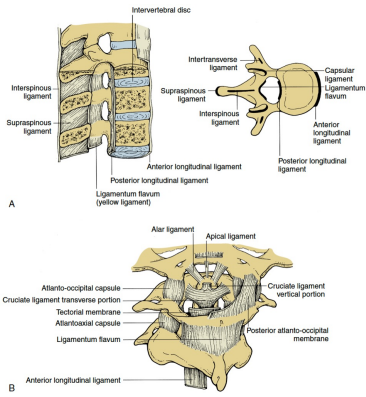
- Multifidus originates from spinous process and inserts on mammillary process 1 level below



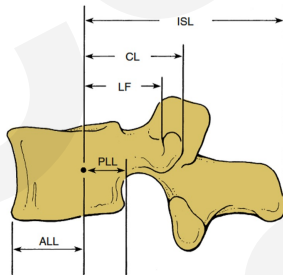
Spinal Biomechanics Ligaments

- Permit smooth movement with a minimum of applied force within physiological range
- Offer protection for loading outside physiological range
 - Stiffness increases by up to 75 times
- Fibre orientation
 - Toe-in region of stress-strain curve
- Viscoelastic properties
 - Stiffness proportional to de/dt
- Function
 - Transfer of load along the spine
 - Restrict movement of spine
 - Prevent overloading of discs

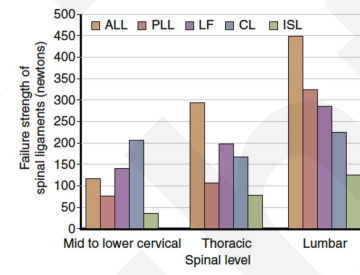




Ligament Lever Arms



Ligament Strength



Intervertebral Disc

- **NUCLEUS PULPOSUS**
 - Water 75-80%
 - GAGS. Hydrated Aggregates
 - Hydrostatic structure
- **ANNULUS FIBROSUS**
 - fibrocartilagenous structure with different "mesh-type" layers



Spinal Biomechanics Discs

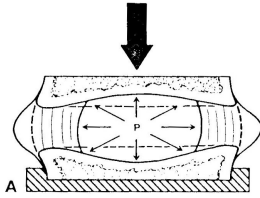
- Biomechanical function
 - Permit movement between adjacent vertebrae
 - Act as a shock absorber
- Predominately loaded in axial direction
 - Can be considered analogous to a pressure vessel
 - Pressurised nucleus prevents the annulus buckling
- Annulus also limits shear and traction motions between adjacent vertebrae
 - As a result of fibre orientation
- Prolonged loading leads to loss of fluid from the annulus and reduction in disc height
 - Diurnal variation in both height and spinal motion





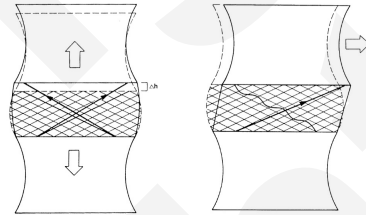
Spinal Biomechanics Discs

- When loaded, discs act like a (thick walled) pressure vessel

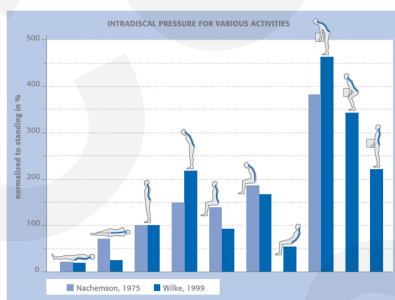


Spinal Biomechanics Discs

- Fibre orientation is also important in resisting relative motion of adjacent vertebrae



Disc Pressures

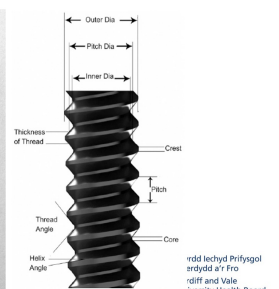
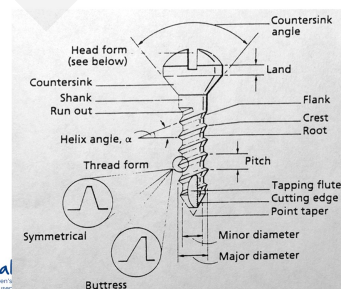


AO Principles

- Anatomic Reduction
- Stable Internal Fixation
- Atraumatic Technique
- Early Active Mobilisation

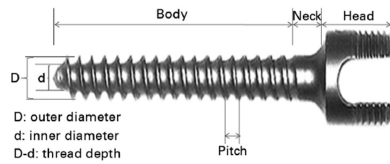


Screw Terminology





Pedicle Screws



Pedicle Screws Key Facts

- Outer diameter = pullout strength
- Inner diameter = fatigue strength
- Avoid dorsal cortex damage during insertion
- Converge screws / good length
- Augmentation in revision / osteoporosis
- Trajectory parallel / caudal to superior endplate
- Straight insertion in sagittal plane strongest stability
- Transverse connectors increase rotational stability



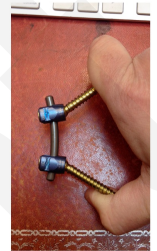
Pedicle Screws - Pullout

- Quantity and quality bone between threads:
 - Increase outer diameter
 - Decrease inner diameter
 - Shorter pitch
 - Stronger bone
 - Increase length
 - Not insertional torque
- 60% pullout 80% longitudinal stiffness in pedicle (vs VB)
- Depth to 80% best
- Converge by 30° increases pullout 30%
- Unknowns:
 - Double lead, dual thread, conical, cylindrical

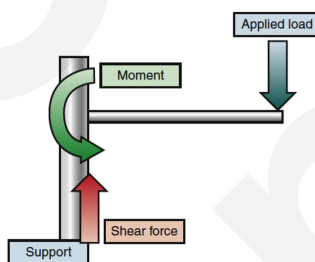


Pedicle Screws

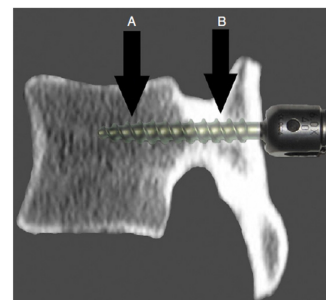
- Fatigue
 - Monoaxial = neck weakest
 - Polyaxial = head screw coupling weakest
- Strongest Construct
 - Pedicle screws with anterior strut with anterior plate



Cantilever Beam



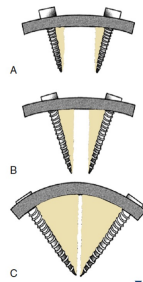
Shear Stresses Canc / Cortical





Triangulation Effect

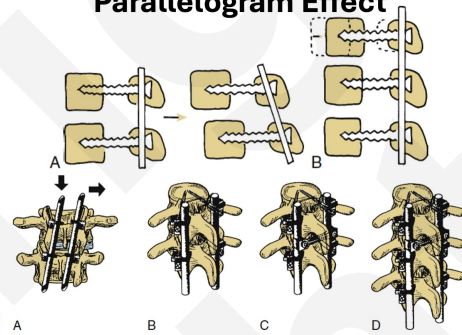
- Reduce Pullout
- Lengthen screws
- Increase Angulation



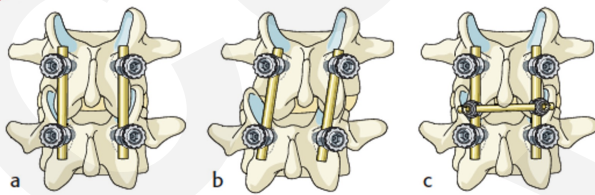
Bwrdd Iechyd Prifysgol
Caerdydd a'r Fro
Cardiff and Vale
University Health Board



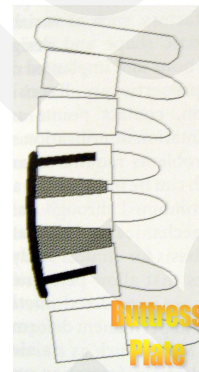
Parallelogram Effect



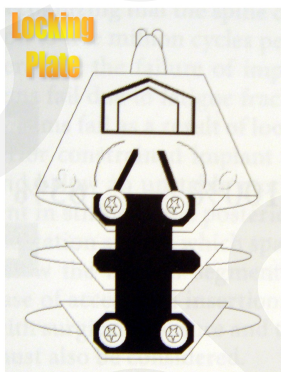
Bwrdd Iechyd Prifysgol
Caerdydd a'r Fro
Cardiff and Vale
University Health Board



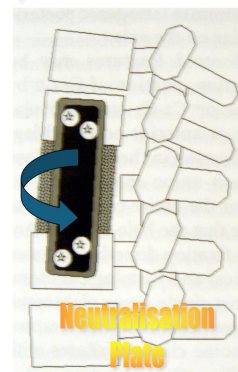
Bwrdd Iechyd Prifysgol
Caerdydd a'r Fro
Cardiff and Vale
University Health Board



Bwrdd Iechyd Prifysgol
Caerdydd a'r Fro
Cardiff and Vale
University Health Board

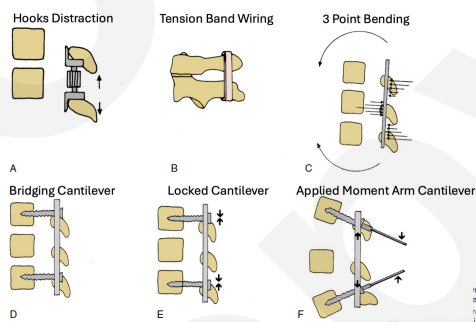
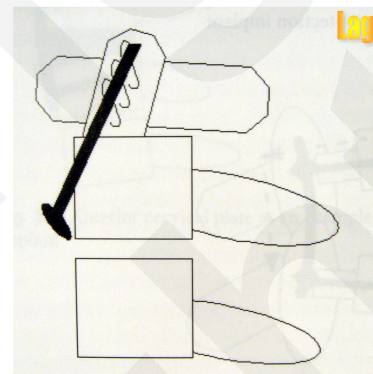
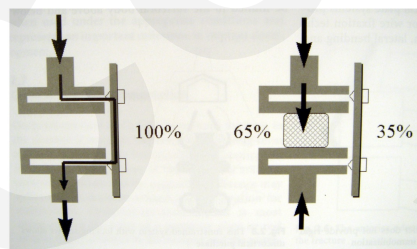
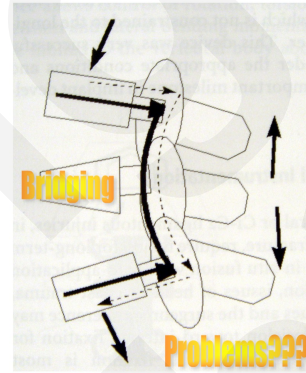
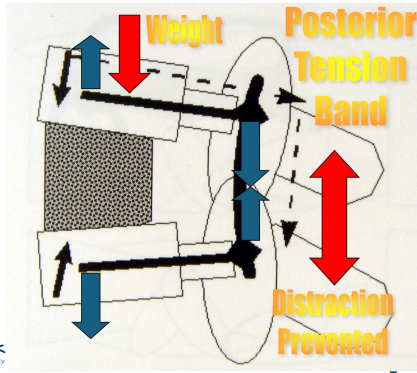


Bwrdd Iechyd Prifysgol
Caerdydd a'r Fro
Cardiff and Vale
University Health Board

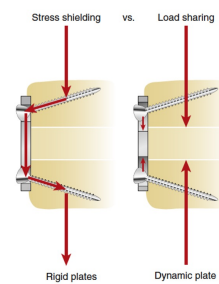


Bwrdd Iechyd Prifysgol
Caerdydd a'r Fro
Cardiff and Vale
University Health Board



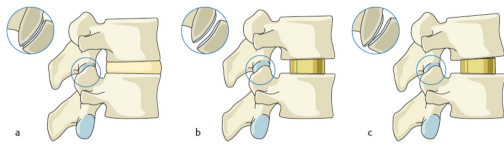


Static vs Dynamic

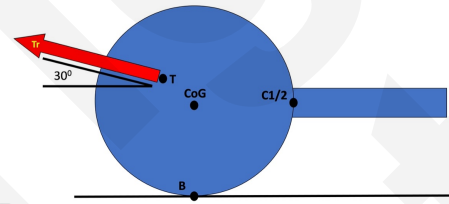




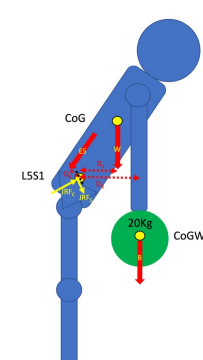
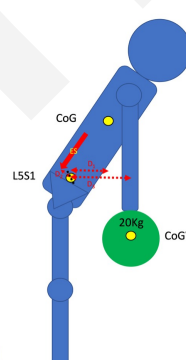
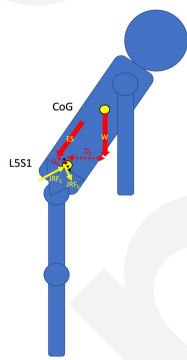
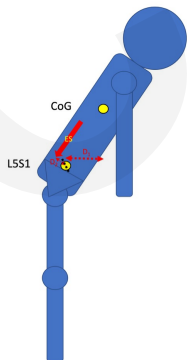
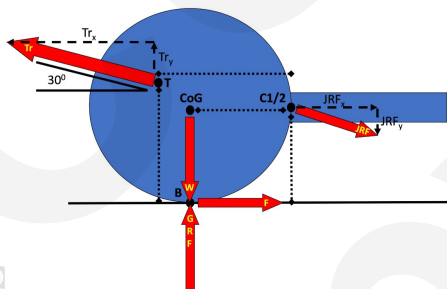
Avoid Distraction



Halo forces

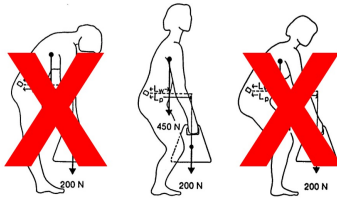


Halo forces





Spinal Biomechanics Lifting



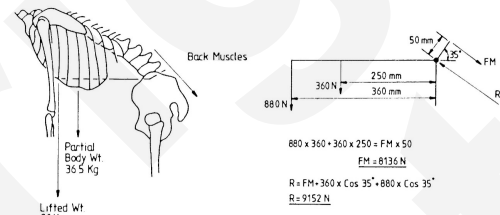
TOTAL FORWARD-BENDING MOMENT = 192.5 Nm

TOTAL FORWARD-BENDING MOMENT = 151 Nm

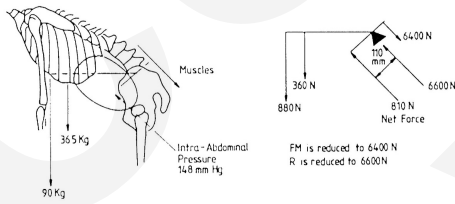
TOTAL FORWARD-BENDING MOMENT = 212.5 Nm



Spinal Biomechanics



Spinal Biomechanics



Spinal Injury

Stable $\longleftrightarrow$ Unstable

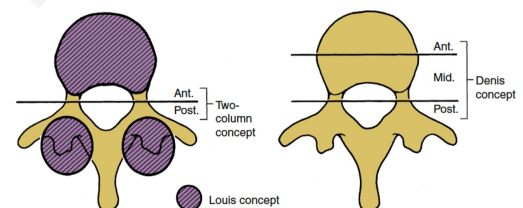


Clinical Instability

- The loss of the ability of the spine under **normal physiological loads** to maintain its pattern of displacement so that there is no initial or additional **neurological deficit**, no major **deformity** and no incapacitating **pain**



Stability





Upper Cervical Instability

- $>8^\circ$ axial rotation C0-1 to one side
- Powers ratio distance BC / OA > 1 (occipito - cervical dislocation)
- Increased odontoid basion distance - the tip of the odontoid should be in line with basion, with the odontoid basion distance 4-5mm adults and up to 10mm in children
- $>1\text{mm}$ C0-1 translation in flexion / extension (this is a specialist investigation, not in the acute trauma setting)
- $>7\text{mm}$ overhang C1-2 (total left and right)
- $>45^\circ$ axial rotation C1-2 to one side
- Atlantodens interval $>5\text{mm}$ (should be $<3\text{mm}$)



Lower Cervical Instability

- Horizontal vertebral body translation $>3.5\text{mm}$ or 20%
- Difference in intervertebral angulation between adjacent levels $>11^\circ$
- Vertebral body height loss
- Disc space $>1.7\text{mm}$
- Facet fracture, subluxation or widening
- Flexion teardrop - small antero-inferior body fracture



Thoracolumbar Instability

- Neurological deficit
- Clinical posterior tenderness or deformity
- $>20-30^\circ$ kyphosis (segmental or combined)
- $>30\%$ loss of vertebral height (thoracic)
- $>50\%$ loss of vertebral height (lumbar)
- $>50\%$ canal compromise
- Rotational malalignment
- Fracture dislocation
- Multiple adjacent fractures (combined height loss $>50\%$)
- Scoliosis $>10^\circ$

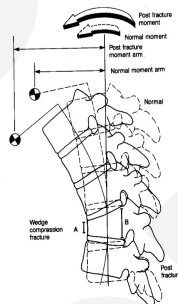


Post Laminectomy Instability

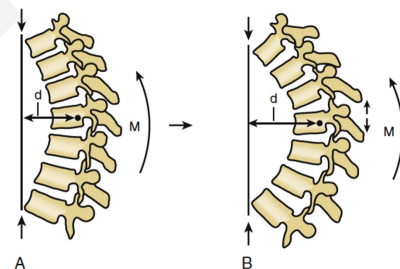
- Denervation of Erector Spinae Muscles
- Anterior displacement of muscle attachments due to scar tissue
- Reduction of posterior moment arm
- Disruption of passive tensile forces exerted by the posterior ligaments



Post Traumatic Kyphosis



$$\text{Moment} = \text{Force} \times \text{Distance}$$



It's like removing your bendy spine..
and replacing it with a metal pole!



Goals for Surgery

**Realign
Stabilize
Decompress
Prevent Late Pain / Deformity**



Neurology

Biomechanics

clearance of canal compromise

Maintain Function



Anterior or posterior surgery

posterior fixation cannot provide anterior column support

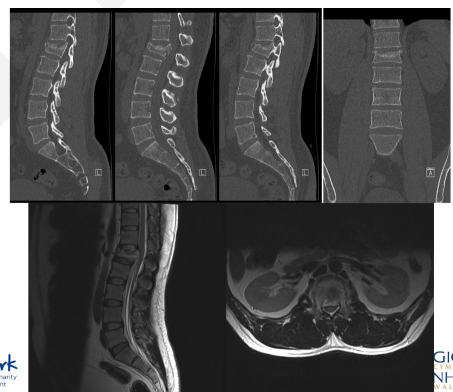
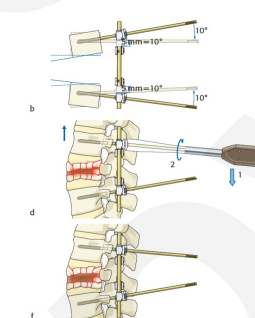
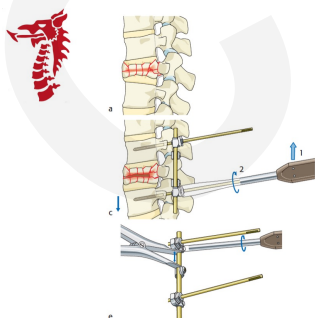
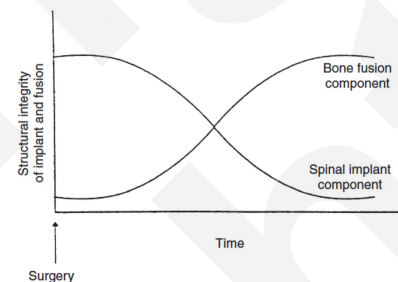
Corpectomy
direct cord decompression
vs. posterior indirect

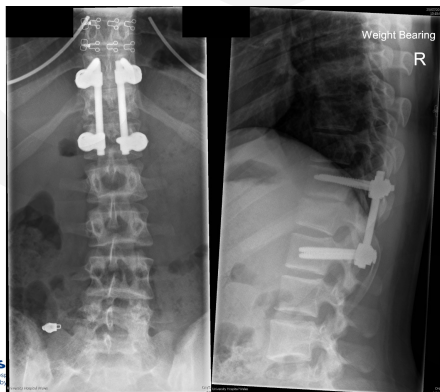
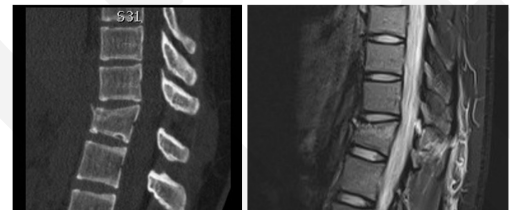
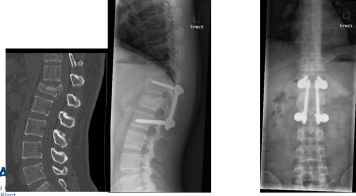
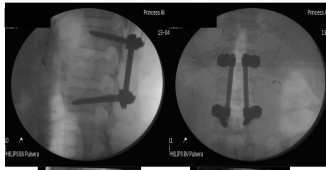
Cons:
Infrequent
Specialist Training

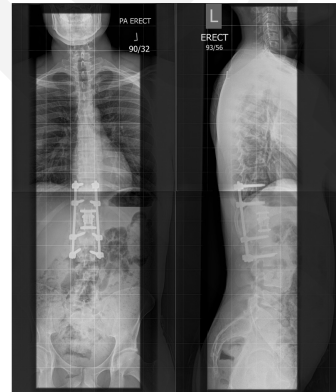
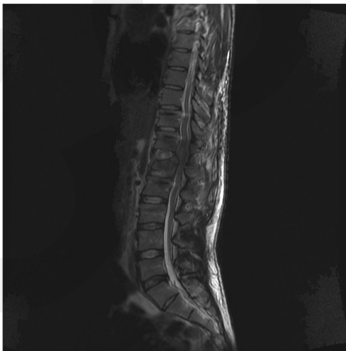
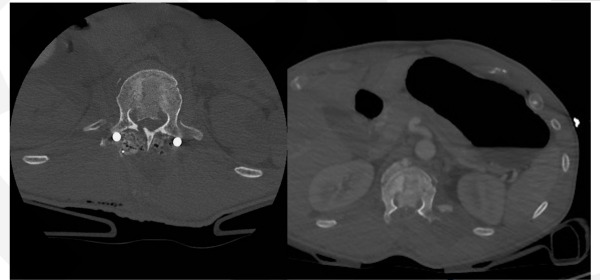
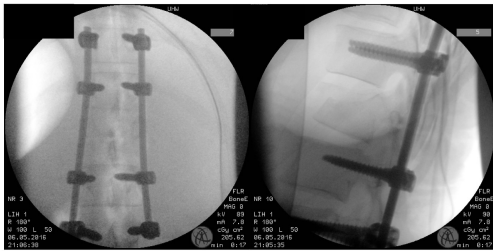
Anterior surgery for significant anterior comminution

correction of deformity

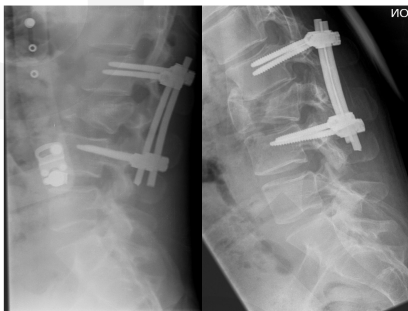
stabilization of instability



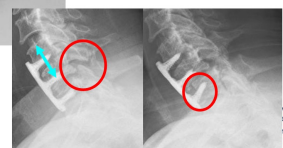
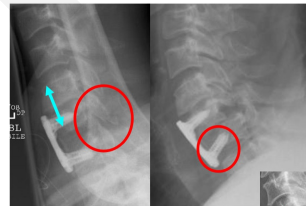




Implant Failure Mechanics

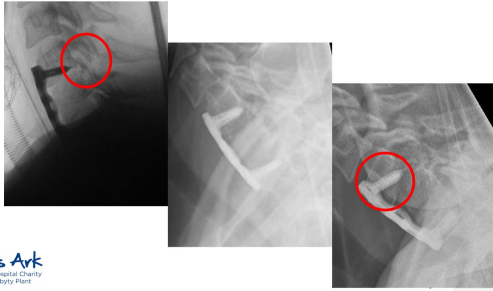


Implant Failure Mechanics

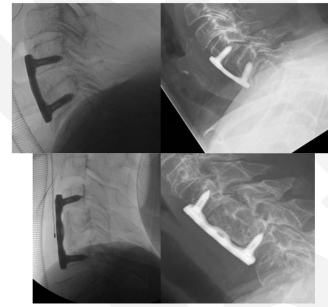




Implant Failure Mechanics



Bone Failure



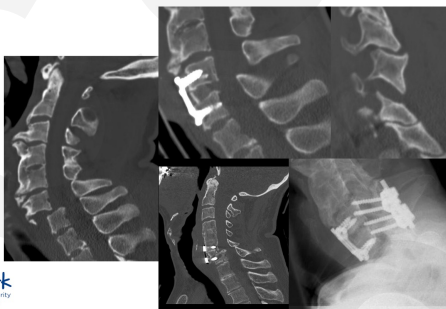
Bwrdd Iechyd Prifysgol
Caerdydd a'r Fro
Cardiff and Vale
University Health Board



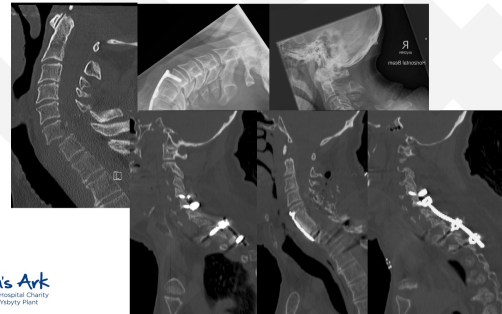
Bwrdd Iechyd Prifysgol
Caerdydd a'r Fro
Cardiff and Vale
University Health Board



Implant Failure Mechanics



Poor Operative Decision



Bwrdd Iechyd Prifysgol
Caerdydd a'r Fro
Cardiff and Vale
University Health Board



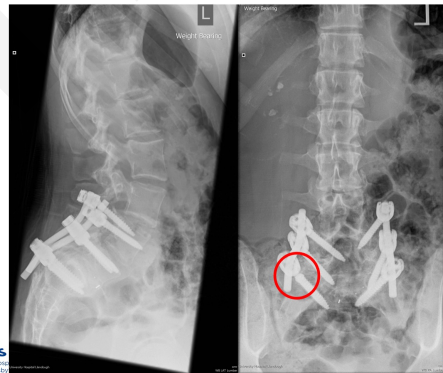
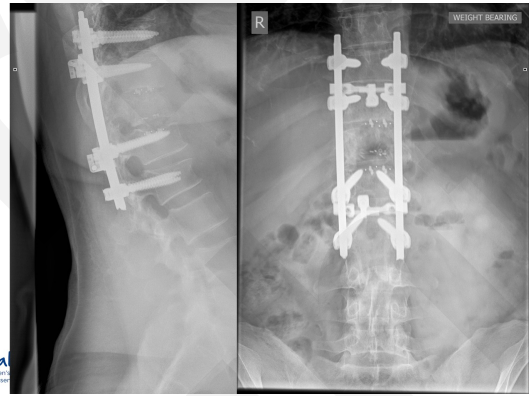
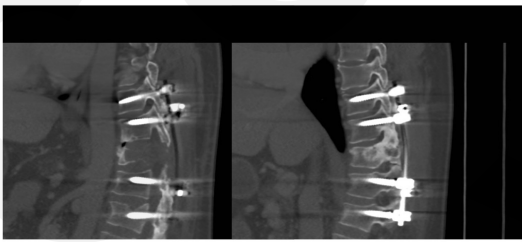
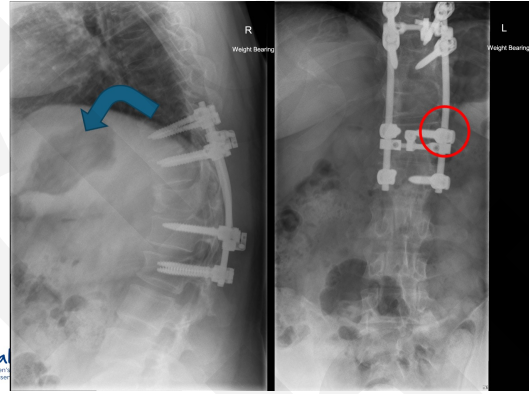
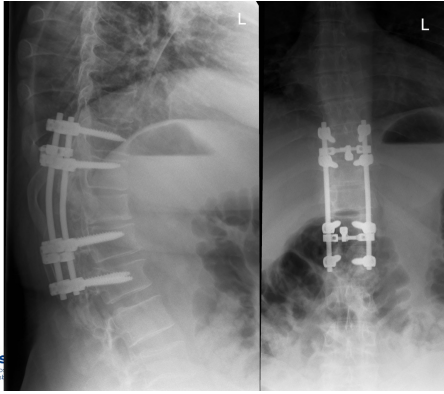
Bwrdd Iechyd Prifysgol
Caerdydd a'r Fro
Cardiff and Vale
University Health Board

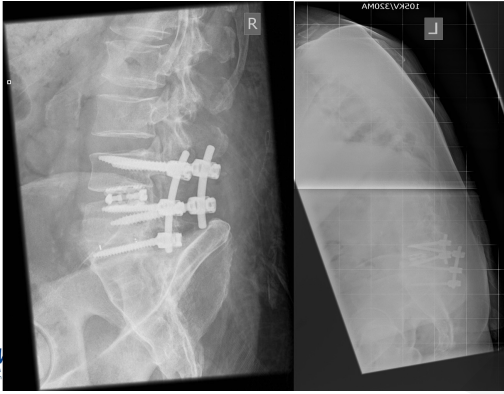


Bwrdd Iechyd Prifysgol
Caerdydd a'r Fro
Cardiff and Vale
University Health Board



Bwrdd Iechyd Prifysgol
Caerdydd a'r Fro
Cardiff and Vale
University Health Board





Bwrdd Iechyd Prifysgol
Caerdydd a'r Fro
Cardiff and Vale
University Health Board



Bwrdd Iechyd Prifysgol
Caerdydd a'r Fro
Cardiff and Vale
University Health Board



Bwrdd Iechyd Prifysgol
Caerdydd a'r Fro
Cardiff and Vale
University Health Board

