Physics of Skeleton

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By the end of this section, you will be able to:

1. What are the major components of bone?
2. What are two advantages of trabecular bone over compact bone?
3. Explain three problems involved with using an x-ray image to measure bone mineral mass in vivo.
4. Diagnose specific types of bone fractures on an X-ray images.
5. What is the function of synovial fluid?

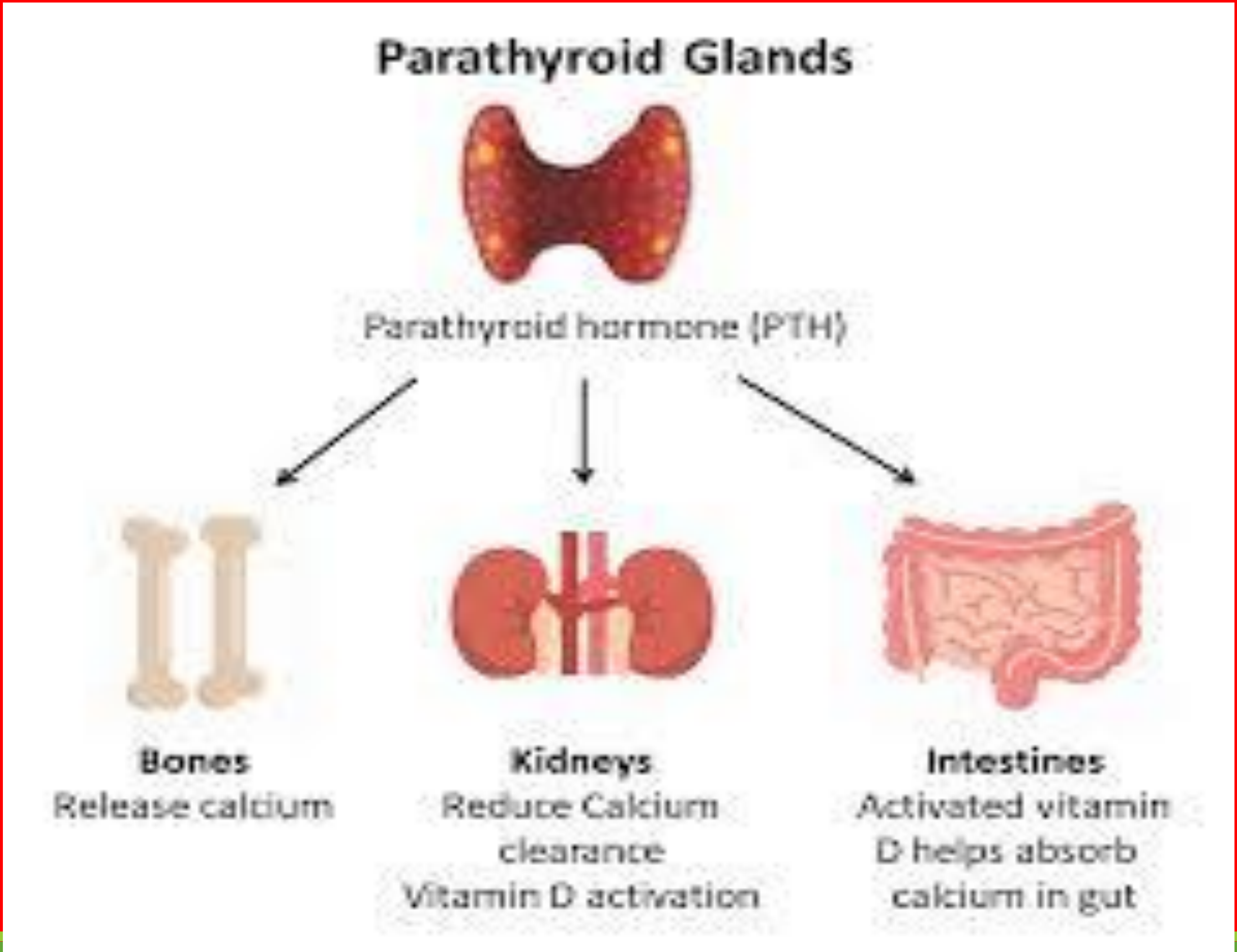
Bone is of interest to medical physics and engineers. Perhaps this organ system of the body appeals most to physical scientists because engineering type problems dealing with static and dynamic leading forces that occur during standing, walking, running, lifting, and forth. Bone has at least six functions in the body

1- Support. Support function is most obvious in the legs. The body's muscle are attached to the bones through tendons and ligaments and the system of bones plus muscles support the body. In old age and in certain disease some of this support structure deteriorates.

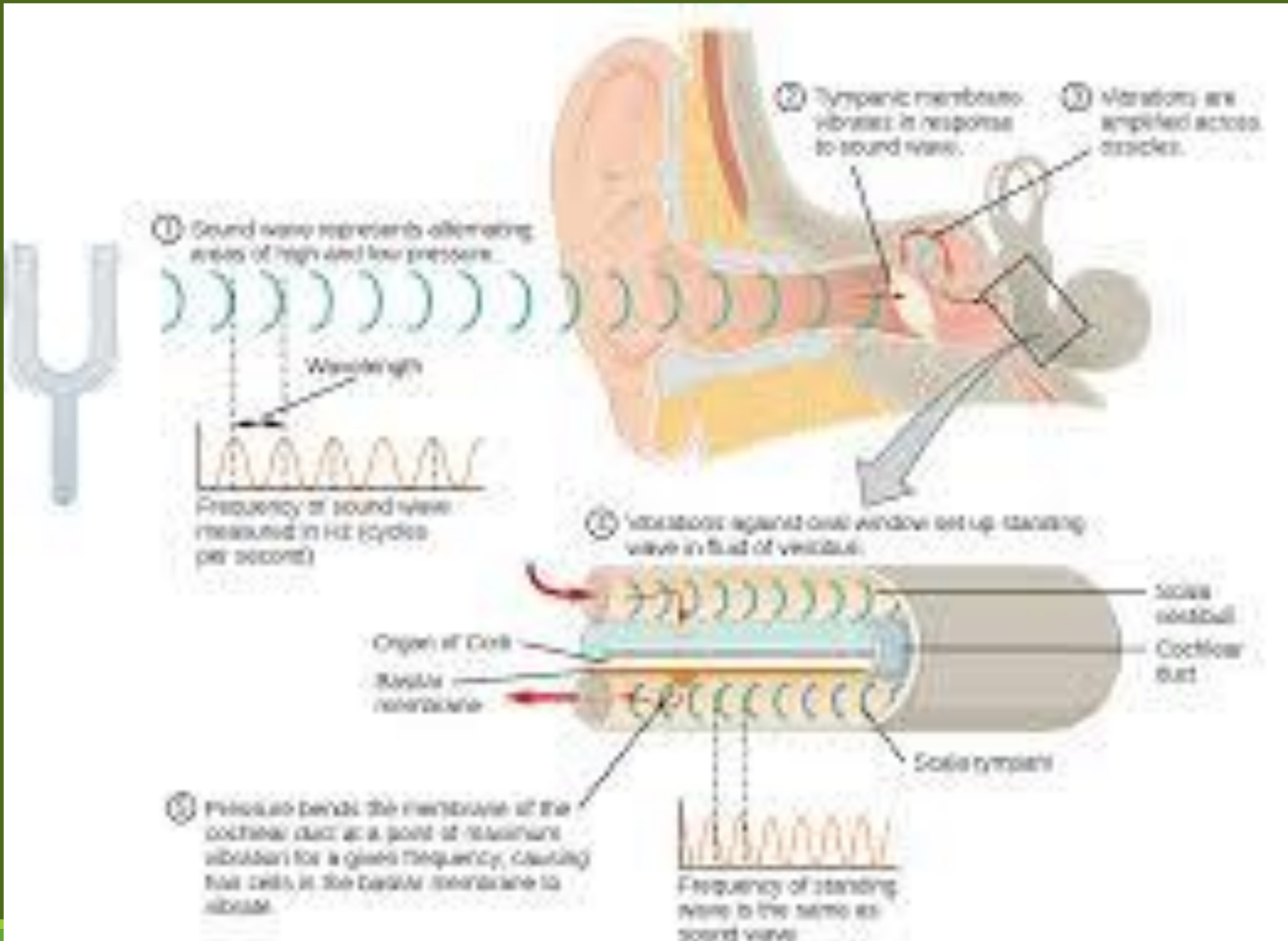
2 - Locomotion. Bone joint permit movement of one bone with respect to another.

3-Protection of various organs. The skull, which protects the brain and several of the most important sensory organs (eyes and ears). The ribs from a protective cage for the heart and lungs.

4-Storage of chemical. The bone acts as a chemical bank for storing elements for future use the body. For example a minimum level of calcium sensor causes the parathyroid glands to release more parathormone into the blood, and this in turn causes the bones to release the needed calcium.


Parathyroid Glands
Parathyroid hormone (PTH)
Bones
Release calcium
Kidneys
Reduce Calcium
clearance
Vitamin D activation
Intestines
Activated vitamin
D helps absorb
calcium in gut

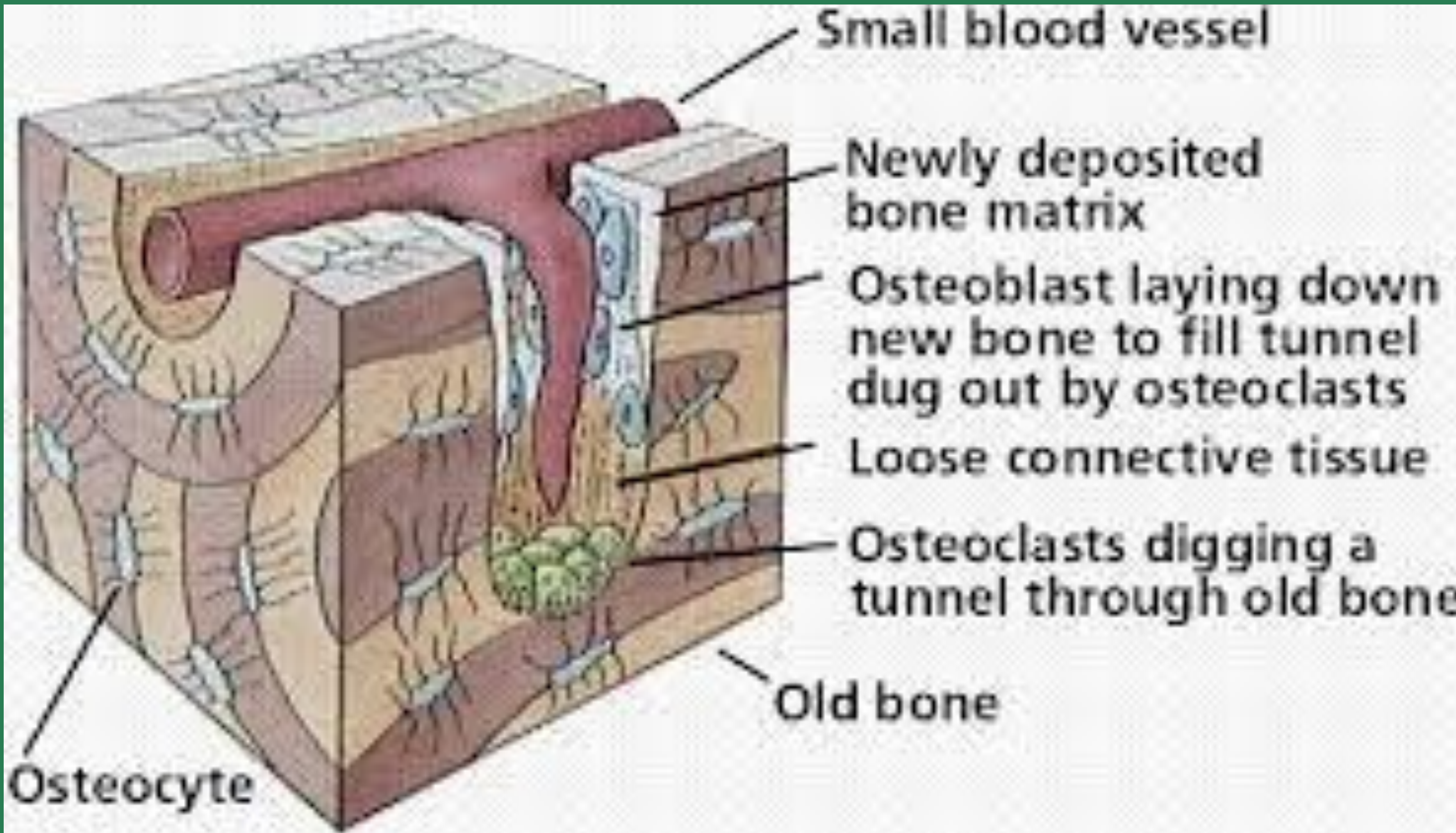
5-Nourishment. The teeth are specialized bones that can cut food.
6-Sound transmission. The smallest bones of the body are the ossicles in middle ear. These three small bones act as lever and provide an impedance matching system for converting sound vibrations in air to sound vibrations in the fluid.



Tympanic membrane vibrates in response to sound wave.
Vibrations are amplified across ossicles.
Sound wave represents alternating areas of high and low pressure.
Wavelength
Frequency of sound wave measured in Hz (cycles per second)
Vibrations against oval window set up standing wave in fluid of vestibule.
Scala vestibuli
Cochlear duct
Organ of Corti
Basilar membrane
Scala tympani

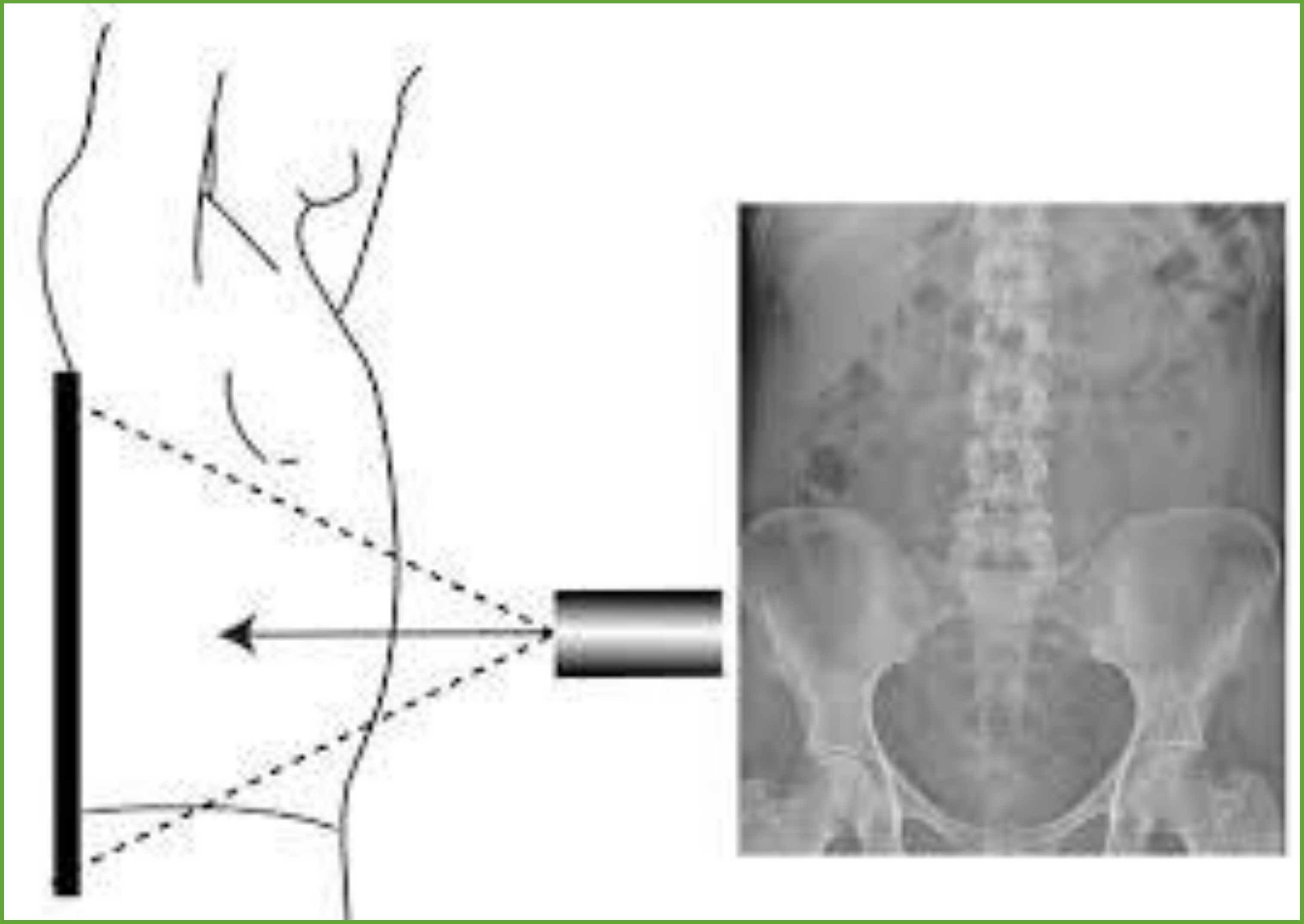
Bone is a living tissue and has a blood supply as well as nerves. Most of the bone tissue is inert, but distributed through it are the osteocytes, cells that maintain the bone in a healthy condition. Cells make up about 2% of the volume of bone. If these cells die (e.g., due to a poor blood supply), the bone dies and it losses some of strength

Since bone is a living tissue it undergoes change throughout life. A continuous process of destroying old bone and building new bone, called bone (remolding), is performed by specialized bone cells. (osteoclasts) destroy the bone, and (osteoblasts) build it.


Small blood vessel
Newly deposited bone matrix
Osteoblast laying down new bone to fill tunnel dug out by osteoclasts
Loose connective tissue
Osteoclasts digging a tunnel through old bone
Old bone
Osteocyte

1. What is Bone made of

The large percentage of calcium in bone. Since calcium has a much heavier nucleus than most elements of the body, it absorbs x-rays much better than the surrounding soft tissue. This is the reason x-rays show bones so well.

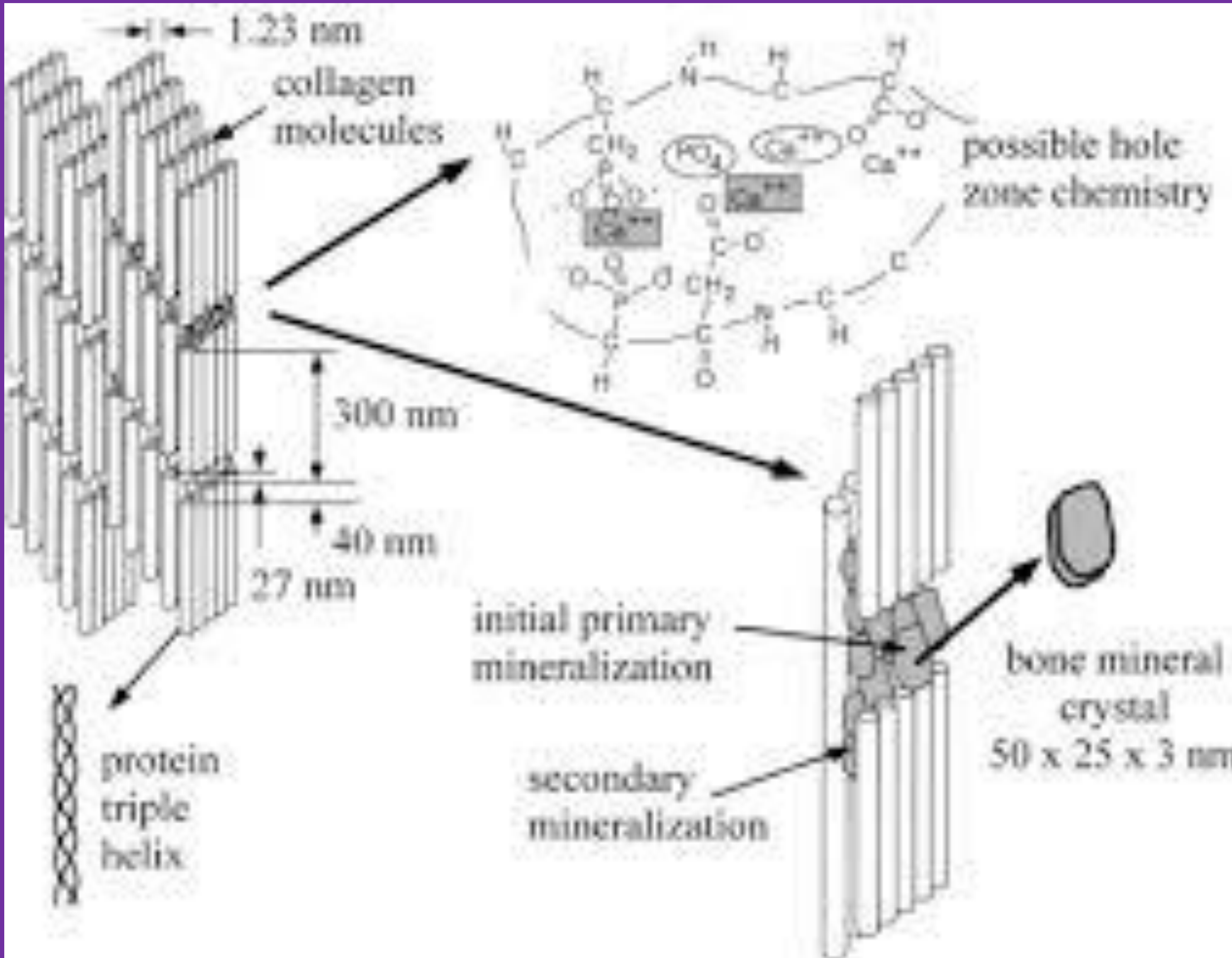


Bone consists of two quite different materials plus water collagen, the major organic fraction, which is about 40% of the weight of solid bone and 60% of its volume, and (bone mineral) the so called inorganic component of bone, which is about 60% of the weight of the bone and 40% of its volume.

Either of these components my be removed from bone, and in each case the remainder, composed of only collagen or bone mineral, will look like the original bone. The collagen remainder is quit flexible, some what a chunk of rubber, it bends easily if it is compressed. When the collagen is removed from the bone,

, the bone mineral remainder is very fragile and can be crushed with fingers. Bone mineral is believed to be made up of calcium hydroxyapaite $Ca_{10}(PO_4)_6(OH)_2$.

Studies using x-ray scattering have indicated that bone mineral crystals are rod shape with diameters of 20 to 70°, and lengths of from 50 t0 100°. Because of small size of the crystals, bone mineral has a very large surface area. The large area of exposed bone mineral crystal permits the bones to interact rapidly with chemicals in the blood and other body fluids.


1.23 nm
collagen molecules
possible hole zone chemistry
300 nm
40 nm
27 nm
initial primary mineralization
bone mineral crystal 50 x 25 x 3 nm
secondary mineralization
protein triple helix

Within a few minutes after small quantity of radioactive fluorine(^{14}F) is injected into a patient, it will be distributed throughout bones of his body.


Healthy Bone
Bone Cancer

Bone tumors not yet visible on an x-ray can be identified by this method. Bone in bone tumor is being destroyed somewhat like a brick house being torn down a brick at a time. When the radioactive fluorine atoms come in contact with this partially destroyed bone, the find many places they can fit in- more so than in normal bone.

2- HOW STRONG ARE YOUR BONES

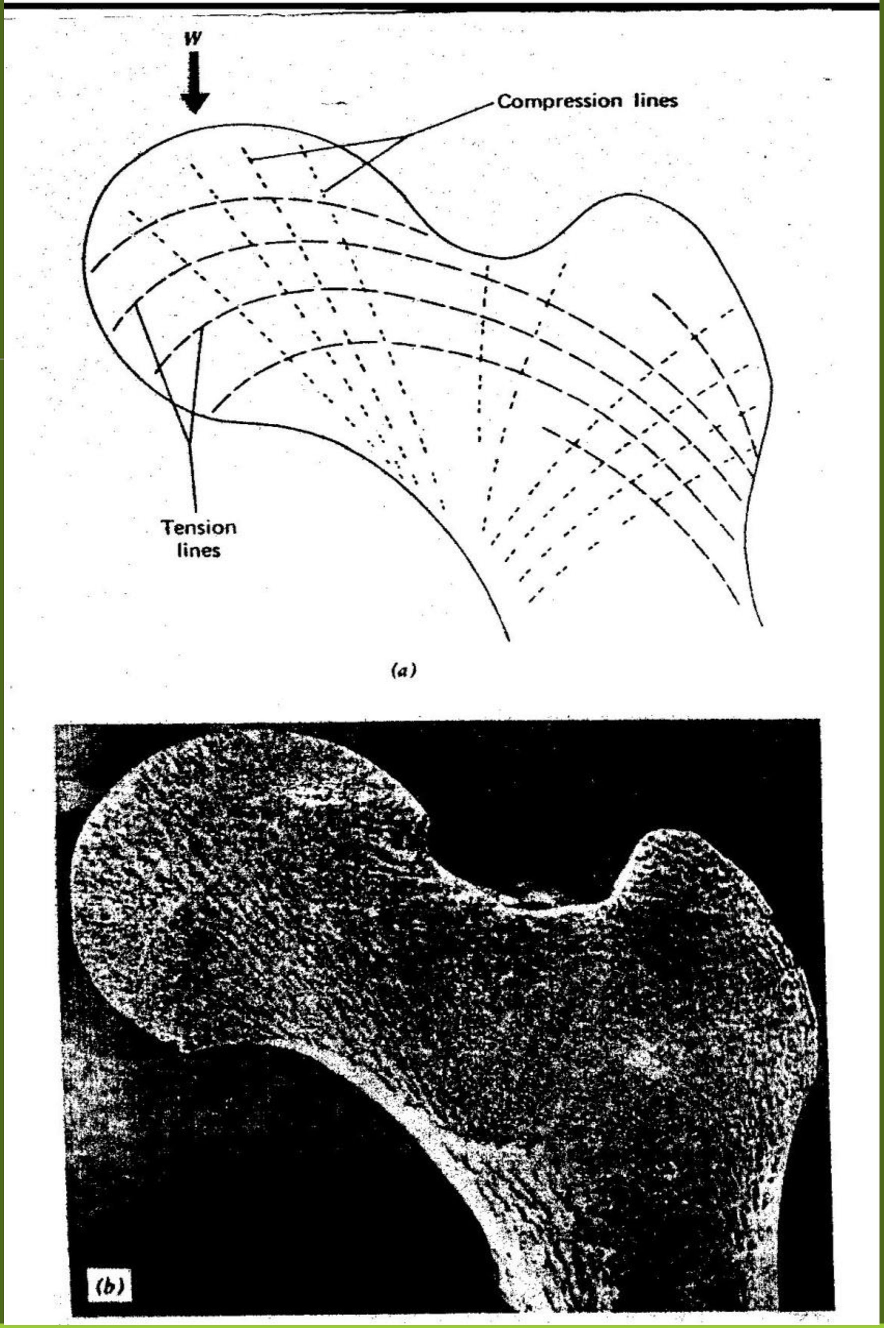
Two Quite Different Types Of Bone. Solid Or Compact, Spongy, Bone Made Up Of Thin Thread – Like Trabecular-

Trabecular Bone Is Found In The Ends Of The Long Bones, While Most Of Compact Bone Is In The Central Shaft. Trabecular Is Weaker Than Compact Bone Due To The Reduced Amount Of Bone In A Given Volume.

What are the advantages of trabecular bone over compact bone.

There are at least two, where a bone is subjected primarily to compressive forces, such as at the ends of the bones, trabecular bone gives the strength necessary with less material than compact bone, also because the trabecular are relatively flexible, trabecular bone can absorb more energy when large forces are involved such as in walking, running and jumping, on other hand, trabecular bone cannot withstand very well the bending stresses that occur mostly in the central portions of long bones.

Figure 1. The head and neck of the femur. The lines of compression and tension due to weight W of The body.



All materials change in length when placed under tension or compression. When a sample of fresh bone placed in a special instrument for measuring the elongation under tension, a curve similar to that in (fig 2) is obtained. The strain $\Delta L/L$ increases linearly at first, indicating that is proportional to the stress (F/A) Hooks law. As the force increases the length increases more rapidly, and the bone breaks at stress of about 120 N/mm2. The ratio of stress to strain in the initial linear portion is Young's modulus Y. That is

$$Y = (L\,F)/(A\,\Delta L)$$

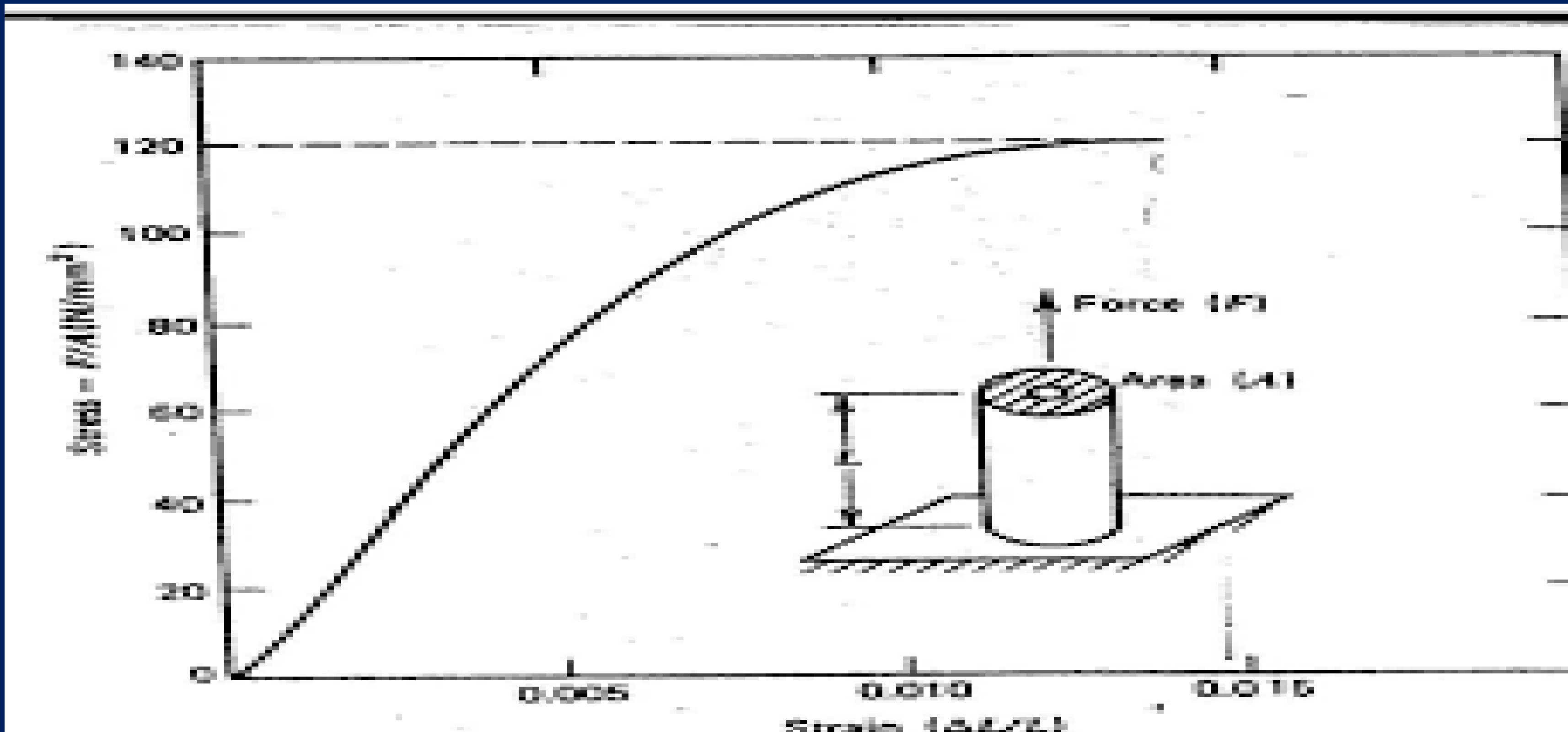
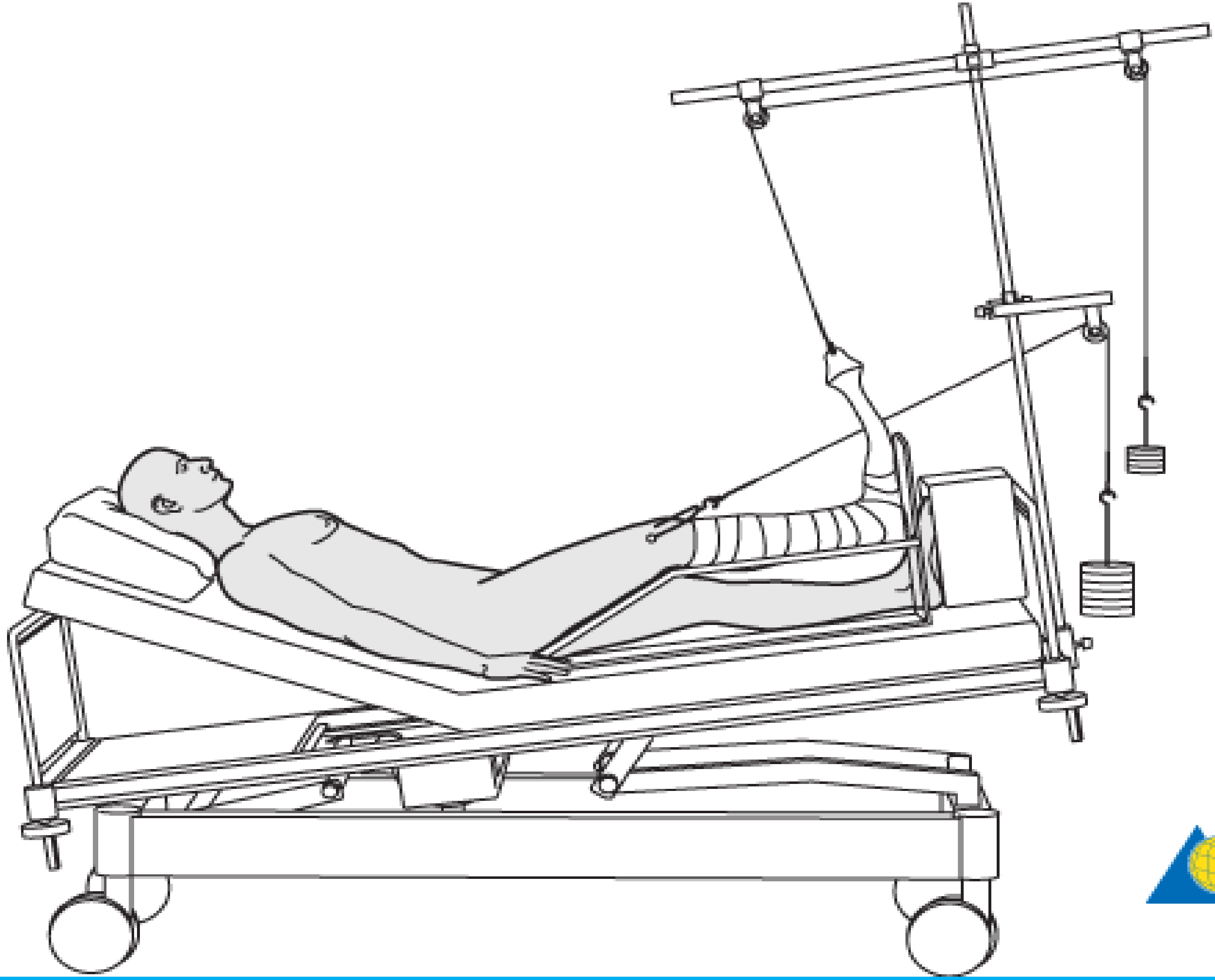


Figure 2. When A Piece Of Bone Placed Under Increasing Tension, Its Strain ΔL/L Increases Linearly At First (Hooks Law) And Then More Rapidly Just Before It Breaks In Two At120 N/Mm^2.

EXAMPLE. Assume a leg has 1.2m shaft of bone with an average cross-sectional area of $3 \times 10^{-4} m^2$. What is amount of shortening when all of the body weight of 700 N is supported on this leg.

Sol.

$$\Delta L = \frac{L\,F}{A\,Y} = \frac{(1.2m)(7 \times 10^{2} N)}{(3 \times 10^{-4})(1.8 \times 10^{10} N/m^2)} = 1.5 \times 10^{-4} m = 0.15 mm$$



The bones don’t normally break due to compression they usually break due to shear (fig3.a) or under tension (fig3.c). A common cause of shear is catching the foot and then twisting the leg while falling.

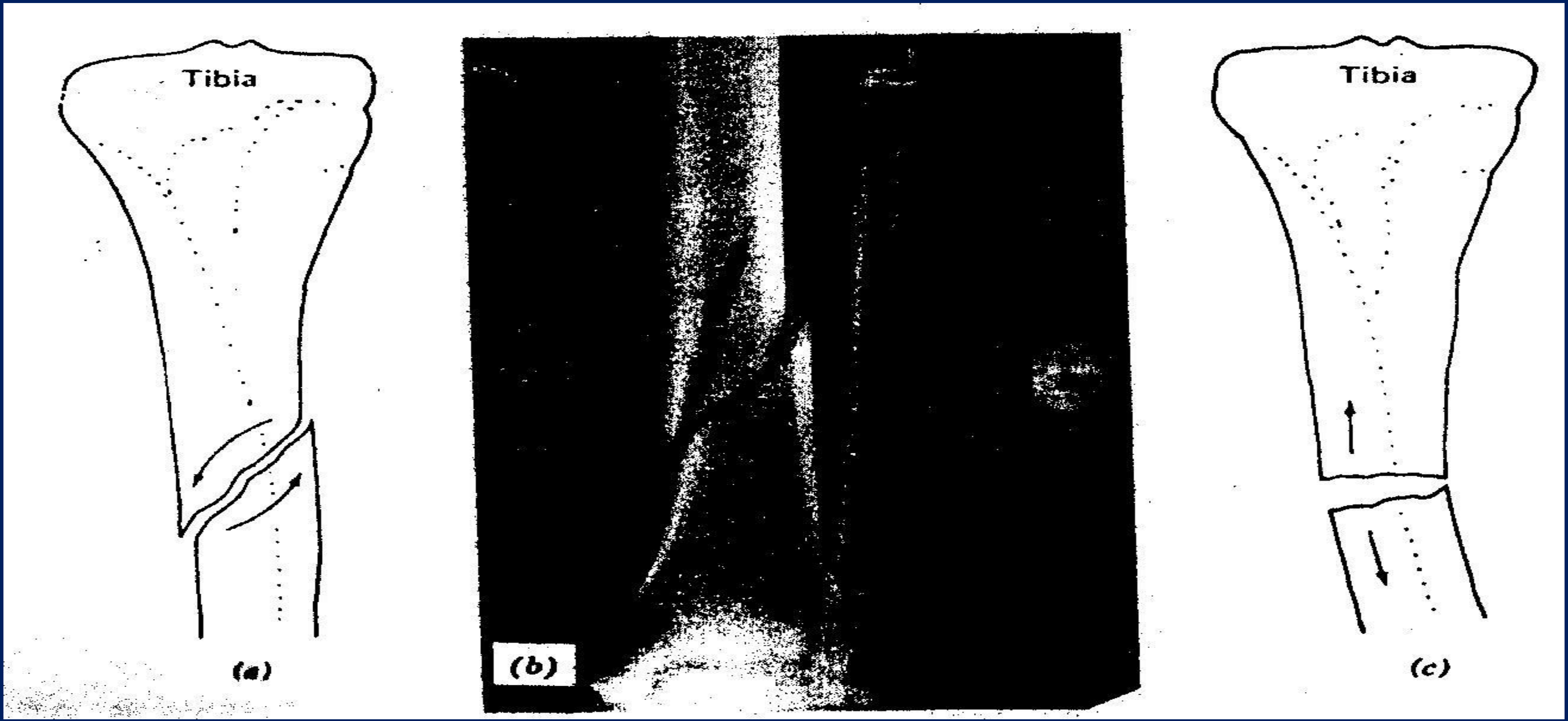
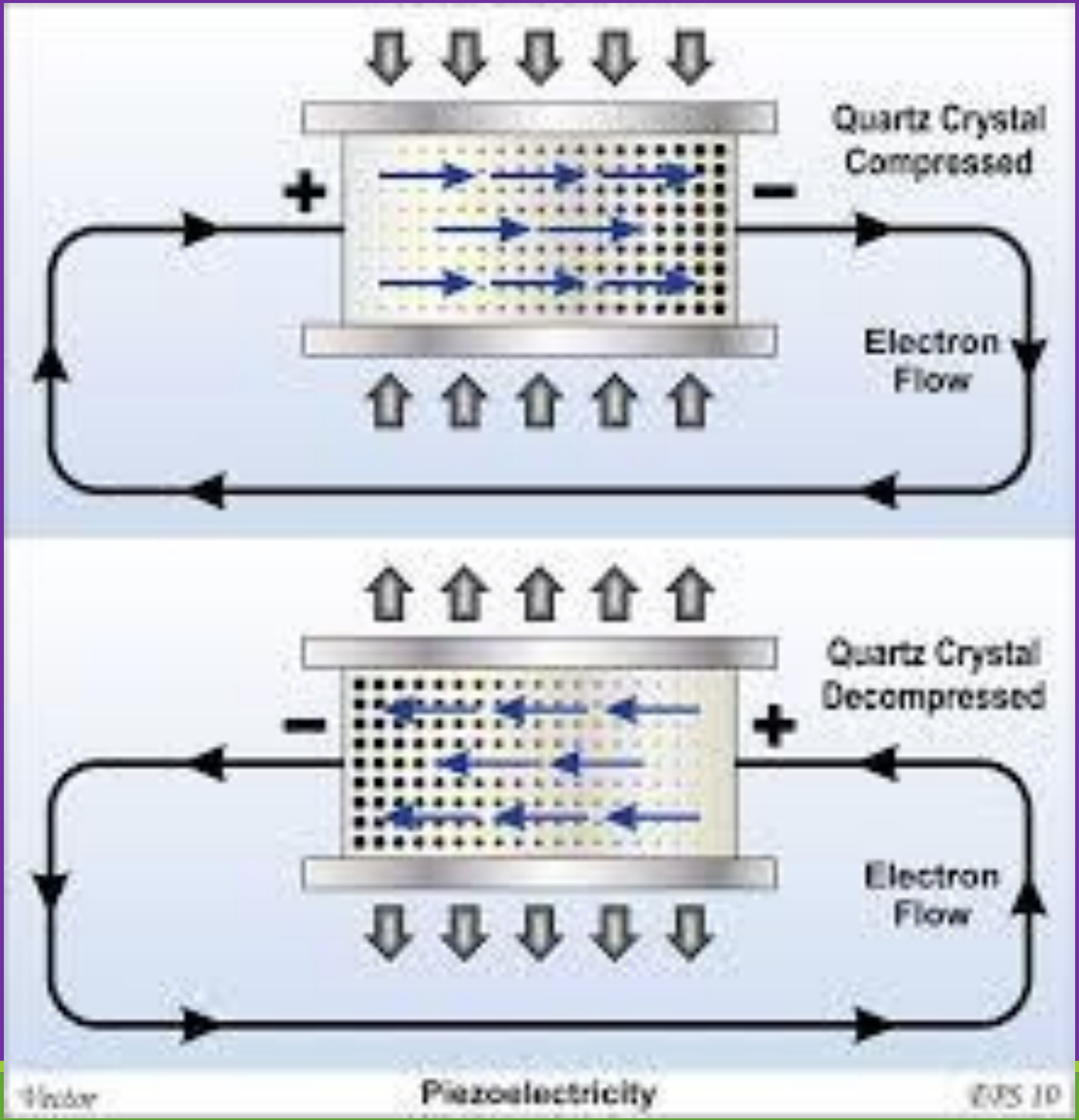


FIGURE.3. FRACTURE OF TIBIA.(A) A SCHEMATIC OF A SPIRAL FRACTURE CAUSED BY SHEAR(TWISTING),(B) AN X-RAY OF A SPIRAL FRACTURE CAUSED BY SHEAR, AND (C) A SCHEMATIC OF A TENSION FRACTURE IN THE TIBIA.

When a bone is fractured, the body can repair it rapidly if the fracture region is immobilized. While the details of growth and repair of bone are not well understood, there is good evidence that local electrical field may play a role. On its surfaces. It has been suggested that is phenomenon (piezoelectricity) may be the physical stimulus for bone growth and repair. Experiments shown that bone heals faster if electrical is applied across break.



Quartz Crystal
Compressed
+
−
Electron
Flow
Quartz Crystal
Decompressed
−
+
Electron
Flow
Piezoelectricity

3-Lubrication of Bone Joints

There are two major diseases that affect the joint-rheumatoid, arthritis, which results in over production of the synovial fluid in the joint and commonly causes swollen joints, and osteoarthritis, a disease of the joint itself. The synovial membrane encases the joint and retains the lubricating synovial fluid.

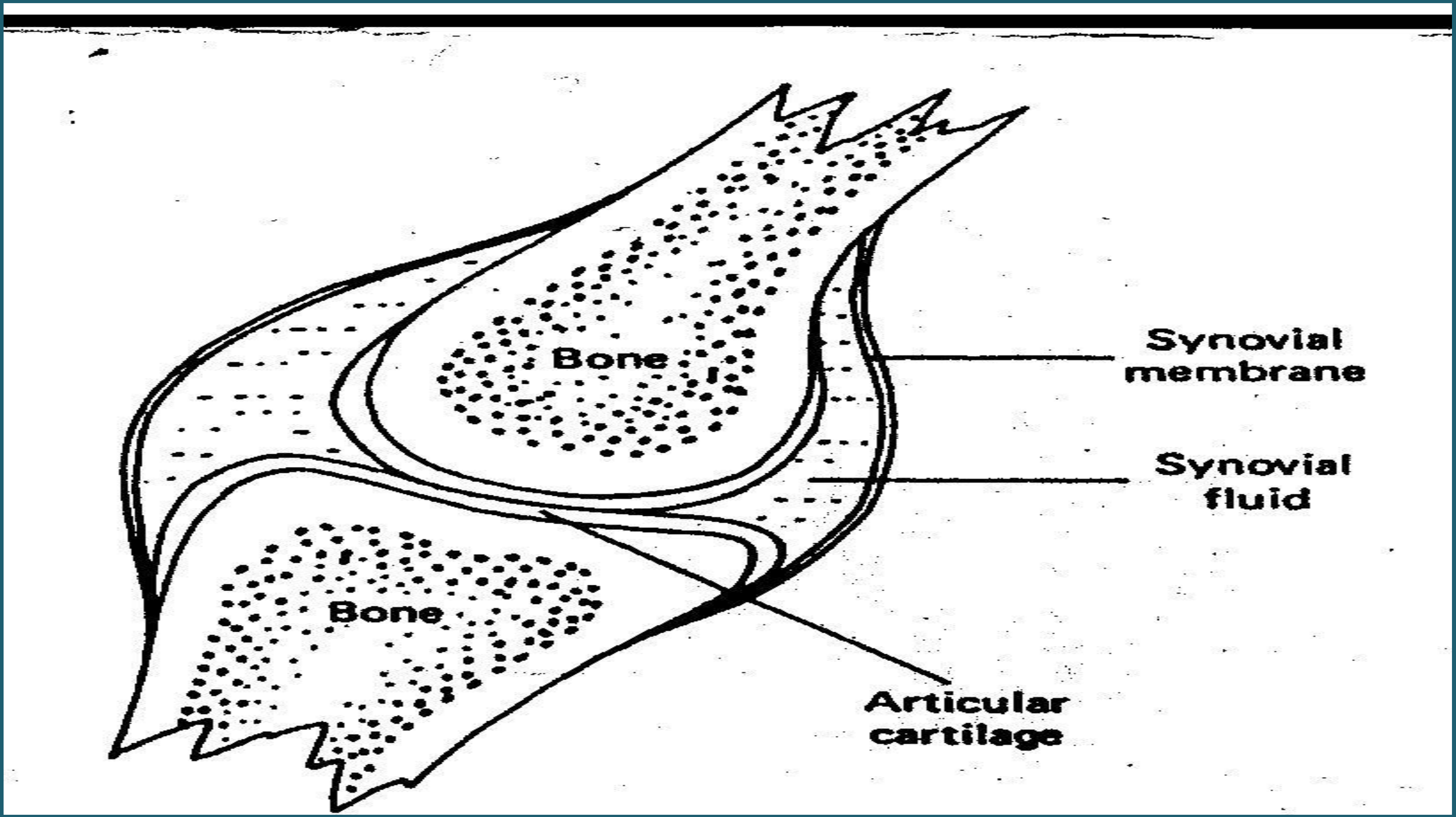


FIGURE 4. THE MAIN COMPONENTS OF A JOINT.

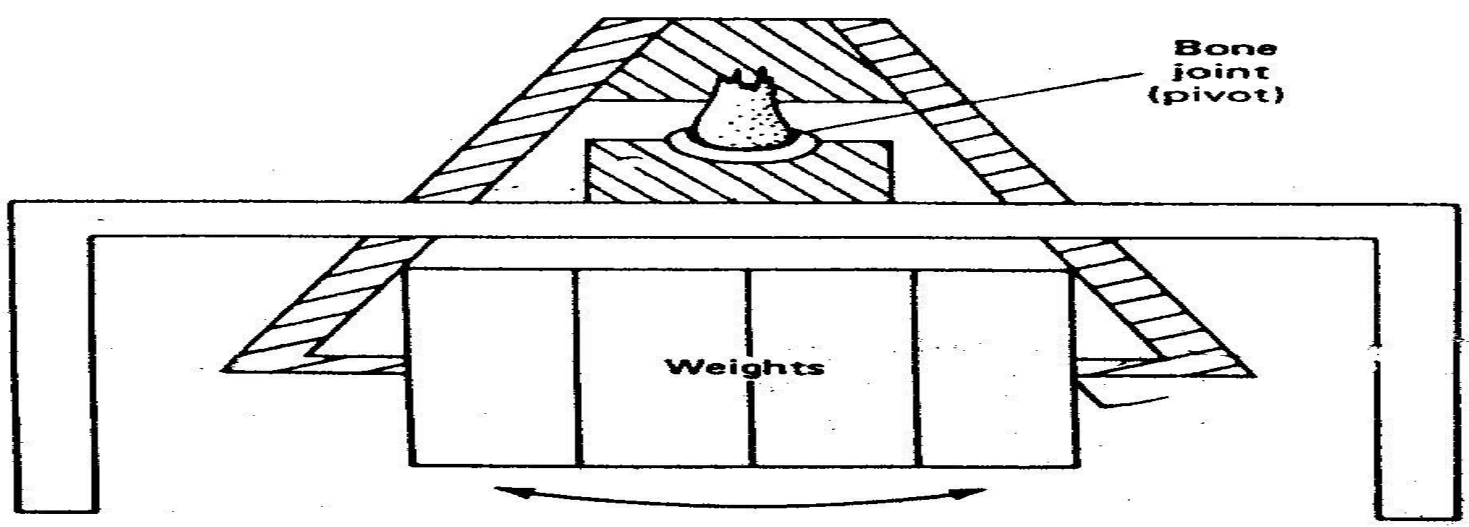
The surfaces of the joint are articular cartilage, smooth somewhat rubbery material that is attached to the solid bone. A disease that involves the synovial fluid, such as rheumatoid arthritis, quickly affects the joint itself.

The surface of articular cartilage is not as smooth as that of a good man-made bearing.

Because of the porous nature of the articular cartilage, other lubricating material is squeezed into joint when it is under its greatest stress-when it needs lubrication the most. The lubricating properties a fluid depend on its viscosity, thin oil is less viscous and better lubricant than thick oil.

The viscosity of synovial fluid decreases under the large shear stress found in the joint. The good lubricating properties of synovial fluid are thought to be due to the presence of hyaluoric acid and mucopolysacharides that deform under load.

The Coefficient Of Friction Is Measured By A Normal Hip Joint From A Fresh Cadaver Was Mounted Upside Down With Heavy Weights Pressing The Head Of The Femur Into The Socket. The Weight On The Joint Could Be Varied To Study The Effects Of Different Loads The Whole Unit Acted Like A Pendulum With The Joint Serving As The Pivot. From The Rate Of Decrease Of The Amplitude With Time The Coefficient Of Friction Was Calculated.



Arrangement for determining the coefficient of friction c
d as the pivot in a pendulum and the decrease in amp
with time is measured.

Measurement of Bone Mineral in the Body

The strength of bone depends to a large extent on the mass of bone mineral present , and the most striking feature in osteoporosis is the lower than normal bone mineral mass. Thus a sample technique to measure bone mineral mass in vivo with good accuracy and precision was sought. It was hoped that such a technique could be used to diagnose osteoporosis before a fracture occurred and also to evaluate various types of therapy for osteoporosis. Since bone mineral mass decreases very slowly, 1 to 2% per year, a very precise technique were needed to show changes.

The idea of using an x-ray image to measure the amount of bone mineral, the major problems of using an ordinary x-ray(fig.6) are

(1) the usual x-ray beam has many different energies, and the absorption of x-rays by calcium varies rapidly with energy in this range of energies.

(2) The relatively large beam contains much scattered when it reaches the film.

(3) The film is a poor detector for making quantitative measurements since it is nonlinear with respect to both the amount and the energy of the x-rays.

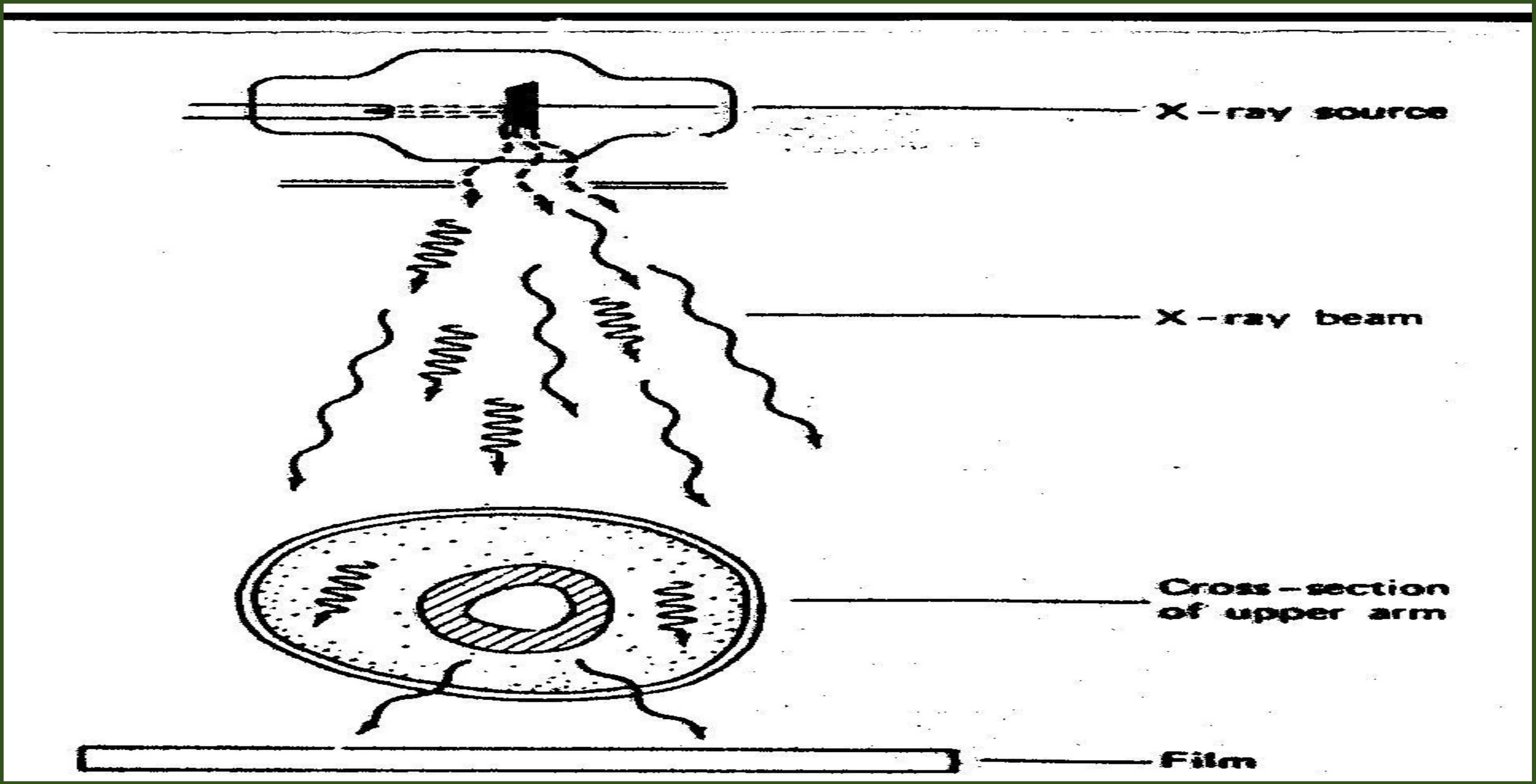


FIGURE 6. CONVENTIONAL X-RAYS ARE NOT USEFUL FOR QUANTITATIVE MEASUREMENT OF BONE MINERAL BECAUSE THE BEAM IS HETEROGENEOUS, THE SCATTER IN THE IMAGE IS UNKNOWN, AND FILM IS NOT A REPRODUCIBLE DETECTOR

An improved technique based on the physical principles called photon absorptiometry is shown in (fig .6). The three problems with x-ray technique were largely eliminated by using

1- Monoenergetic x-ray or gamma source

2- Narrow beam to minimize scatter

3- A scintillation detector

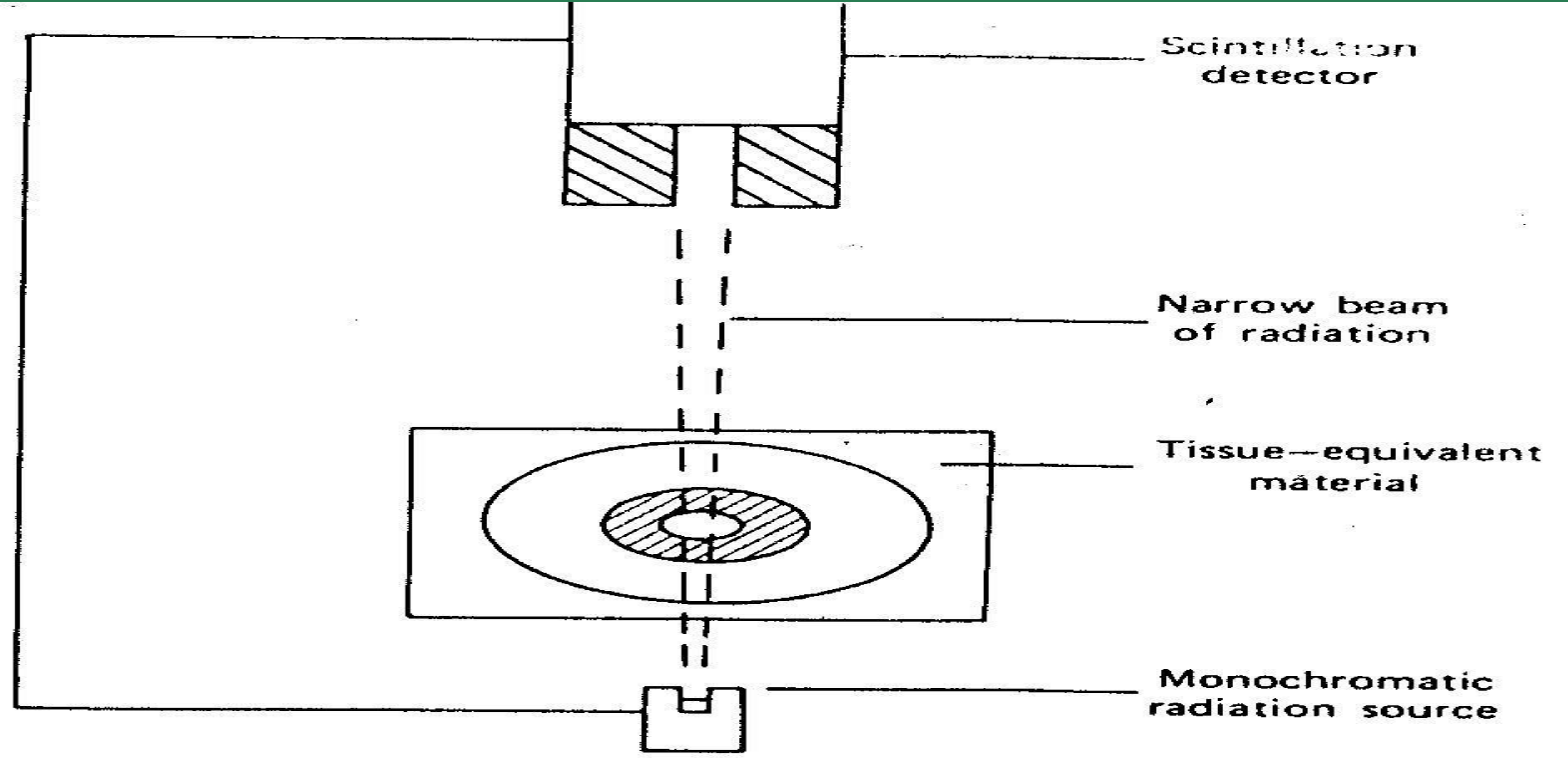


FIGURE 7.THE BASIC COMPONENTS USED IN PHOTON ABSORPTIOMETRY.

A radioisotope that emits essentially only one energy, such as iodine 25 (27Kev)or americium 241 (60Kev), severs as the radiation source: the limb is embedded in a uniform thickness of tissue; and the transmitted fraction of the narrow beam is detected by a scintillation equivalent material-detector.

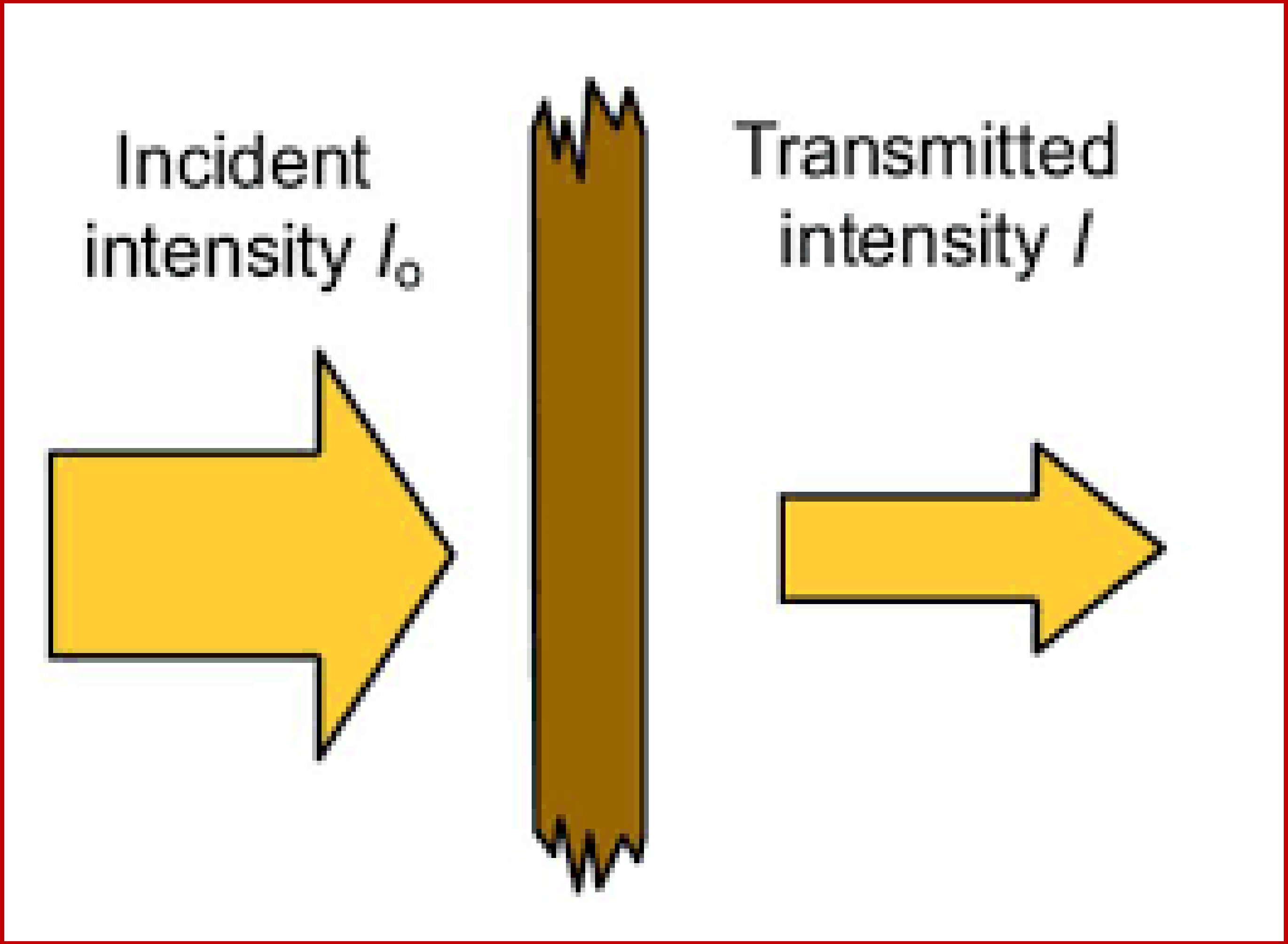

Incident
intensity I_o
Transmitted
intensity I

Figure 8. Shows a graph of the logarithm of the transmitted intensity of the beam (log I), and the intensity before the beam enters the bone is called Io. The bone mineral mass (BM) at any point in the beam is proportional to log (Io/I) and is given by

BM (g/cm^2) = K log (I_o/I) where K is a constant

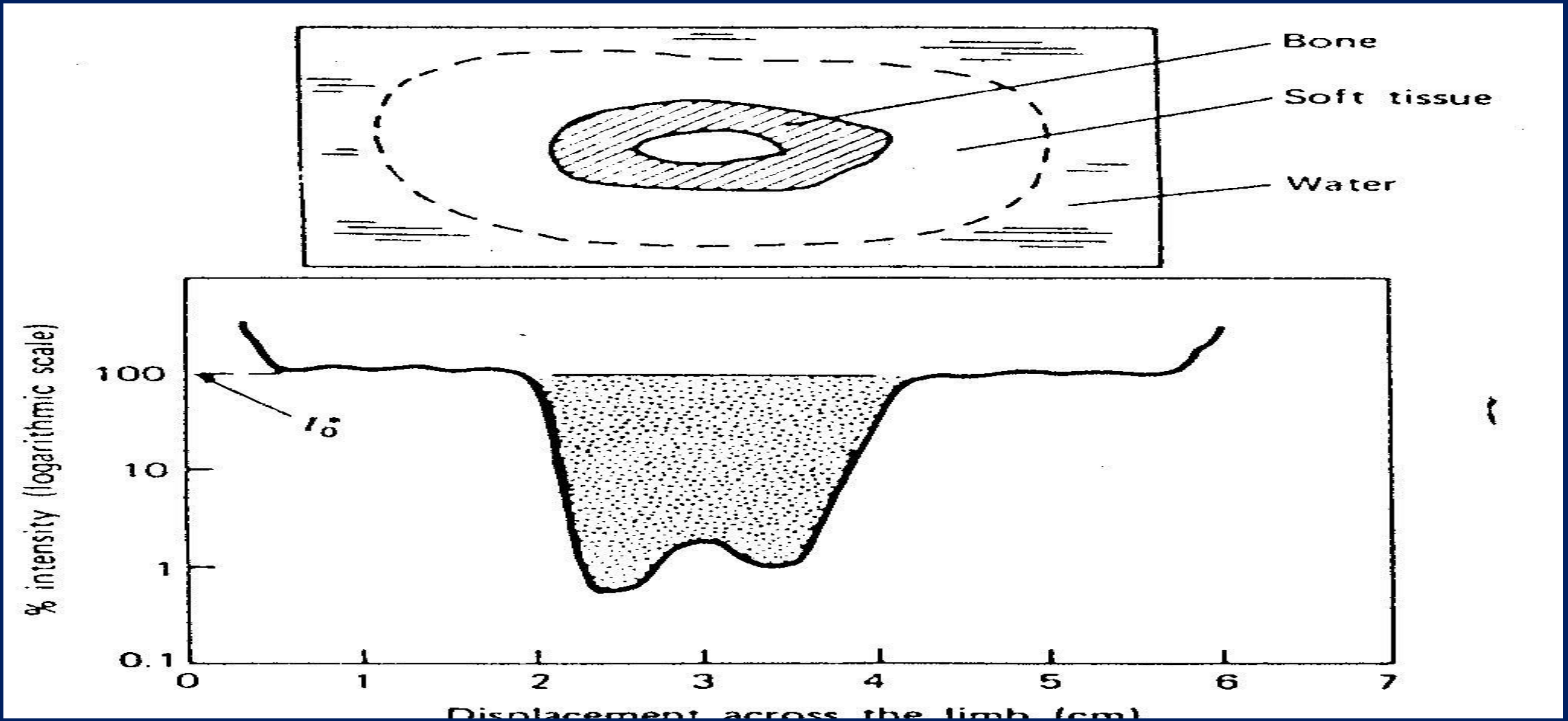


FIGURE 8. THE SHADED AREA IS PROPORTIONAL TO THE BONE MINERAL MASS PER UNIT LENGTH

Another physical technique for measuring bone mineral in vivo takes advantage of the fact that nearly all of the calcium in the body is in the bones. This technique is called in vivo activation. The whole body is irradiated with energetic neutrons that convert a small amount of the calcium and some other elements into radioactive forms that give off energetic gamma rays

Emitted gamma rays are then detected and counted. The gamma rays from radioactive calcium can be identified by their unique energy (fig 9), and the number of them indicates the amount of calcium in the body. The amount of bone mineral is then obtained by multiplying by constant.

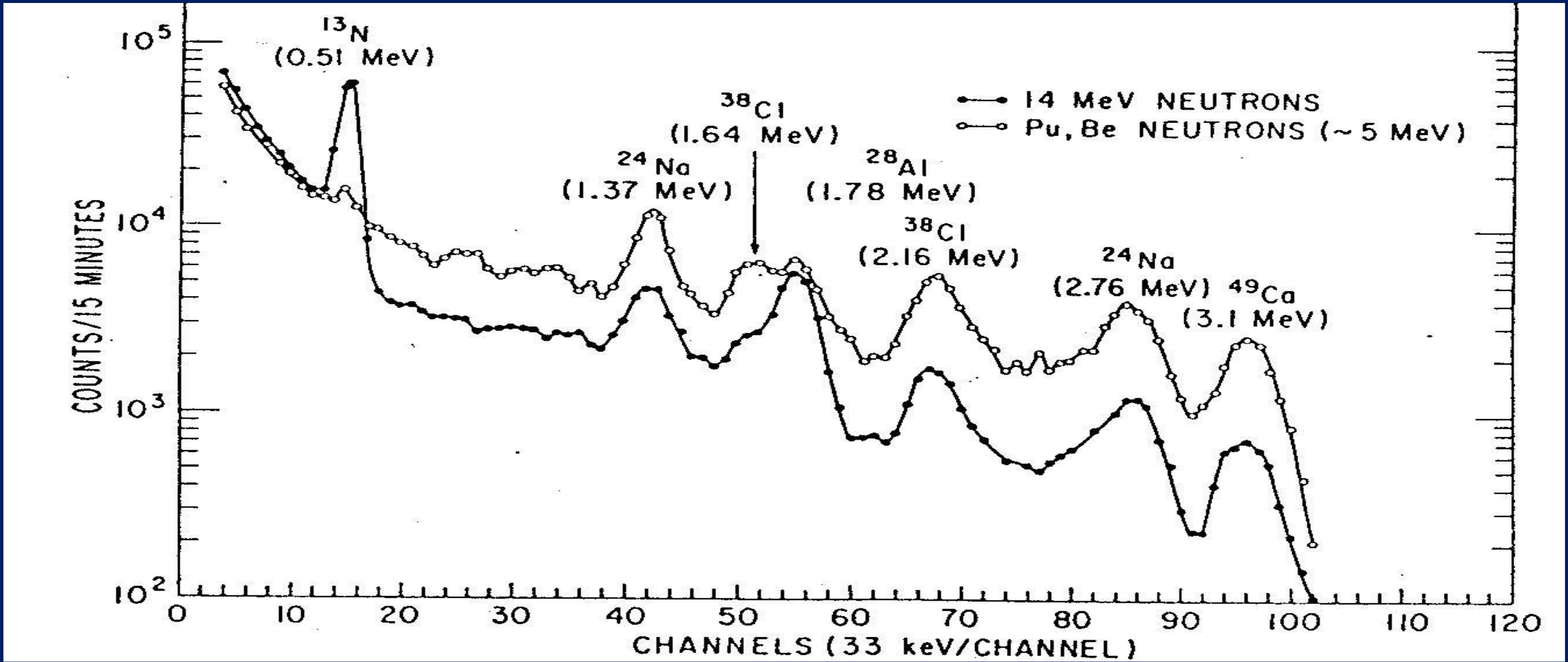


FIGURE 9. A GRAPH OF GAMMA RAY INTENSITIES FROM THE BODY AS A FUNCTION OF ENERGY AFTER WHOLE BODY IRRADIATION. THE RADIOACTIVE ELEMENTS CAUSING THE MAIN GAMMA RAY PEAKS AND THEIR ENERGIES ARE GIVEN. THE AREA UNDER THE PEAK INDICATES THE AMOUNT OF CALCIUM IN THE BODY.

REVIEW QUESTIONS

1- Calculate the maximum tension a bone with a ✖ cross-sectional area of $4cm^2$ could withstand just prior to fracture.

sol ✖

Stress = F/A or = tension/area

120 N/m m^2 = tension / 400 mm^2

tension just prior to fracture =

120 N /m m^2 x 400m m^2 = = 48000N

2- Determine how much a bone 35cm long would elongate under this maximum tension.

Sol

Strain = $\Delta L / L$

0.015 at fracture = $\Delta L / 0.35\ m$

$\Delta L = 0.015 \times 0.35\ m = 0.0052\ m = 5.2\ mm$

Calculate the stress on this bone if the tension force of 10^4 N were applied to it. How much would this bone lengthen?

Sol

Stress = F/A = 10^4N/ 4x 10^{-4}m^2 = 2.5 x 10^7 N/m^2

ΔL =LF /AY = (0.35 m) (10^4N) / (4 x10^{-4}m^2) (1.8 x 10^{10}N/m^2) =

4.9 x 10^{-4}m = 0.49 mm