8: Muscle

Introductory Remarks

Muscle tissue is composed predominantly of cells that are specialised to shorten in length by contraction. This contraction results in movement. It is in this way that virtually all movements within the body, or of the body in relation to the environment, are ultimately produced.

Muscle tissue is made up basically of cells that are called ***myocytes***. Myocytes are elongated in one direction and are, therefore, often referred to as ***muscle fibres***. We shall see, however, that in some cases muscle fibres are made up of several myocytes joined to each other; or of greatly elongated myocytes containing multiple nuclei.

The force generated by contraction of a muscle fibre is transmitted to other structures through connective tissue. Each muscle fibre is closely invested by connective tissue that is continuous with that around other muscle fibres. Because of this fact the force generated by different muscle fibres gets added together. In some cases a movement may be the result of simultaneous contraction of thousands of muscle fibres.

The connective tissue framework of muscle also provides pathways along which blood vessels and nerves reach muscle fibres.

From the point of view of its histological structure muscle is of three types.

(1) The first variety of muscle tissue is present mainly in the limbs and in relation to the body wall. Because of its close relationship to the bony skeleton, this variety is called ***skeletal muscle***. When examined under a microscope, fibres of skeletal muscle show prominent transverse striations. Skeletal muscle is, therefore, also called ***striated muscle***. Skeletal muscle can normally be made to contract under our will (to perform movements we desire). It is, therefore, also called ***voluntary muscle***. Skeletal muscle is supplied by somatic motor nerves.

(2) The second variety of muscle is present mainly in relation to viscera. It is seen most typically in the walls of hollow viscera. As fibres of this variety do not show transverse striations it is called ***smooth muscle***, or ***non-striated muscle***. As a rule, contraction of smooth muscle is not under our control; and smooth muscle is, therefore, also called ***involuntary muscle***. It is supplied by autonomic nerves.

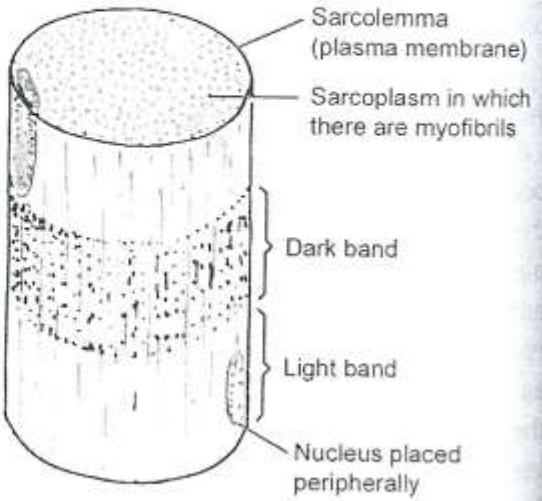

Fig. 8.1. Scheme to show the structure of a muscle fibre.

(3) The third variety of muscle is present exclusively in the heart and is called *cardiac muscle*. It resembles smooth muscle in being involuntary; but it resembles striated muscle in that the fibres of cardiac muscle also show transverse striations. Cardiac muscle has an inherent rhythmic contractility the rate of which can be modified by autonomic nerves that supply it.

It will be obvious that the various terms described above are not entirely satisfactory, there being numerous contradictions. Some 'skeletal' muscle has no relationship to the skeleton being present in situations such as the wall of the oesophagus, or of the anal canal. The term striated muscle is usually treated as being synonymous with skeletal muscle, but we have seen that cardiac muscle also has striations. In many instances the contraction of skeletal muscle may not be strictly voluntary (e.g., in sneezing or coughing; respiratory movements; maintenance of posture). Conversely, contraction of smooth muscle may be produced by voluntary effort as in passing urine.

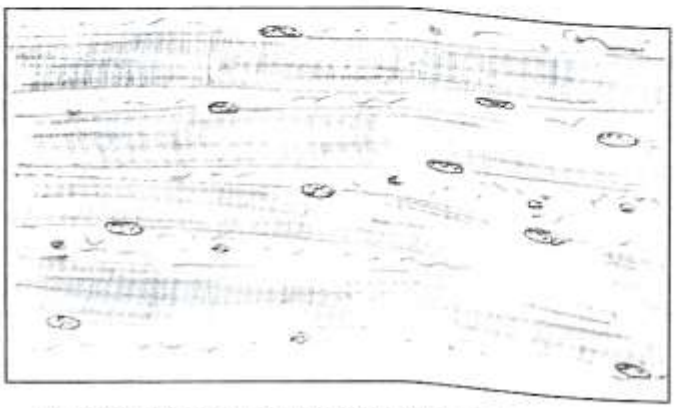

Fig. 8.2a. Skeletal muscle seen in longitudinal section (drawing).

Skeletal Muscle

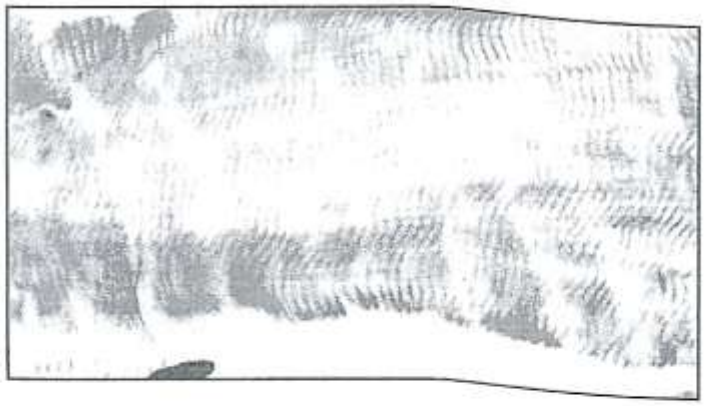

Fig. 8.2b. Skeletal muscle seen in longitudinal section (photomicrograph).

Elementary Facts about Skeletal Muscle

Skeletal muscle is made up essentially of long, cylindrical 'fibres'. The length of the fibres is highly variable, the longest being as much as 30 cm in length. The diameter of the fibres also varies considerably (10 to 60 μm: usually 50-60 μm). Each 'fibre' is really a syncytium with hundreds of nuclei along its length. (The 'fibre' is formed, during development, by fusion of numerous myoblasts). The nuclei are elongated and lie along the periphery of the fibre, just under the cell membrane (which is called the ***sarcolemma***). The cytoplasm (or ***sarcoplasm***) is filled with numerous longitudinal fibrils that are called

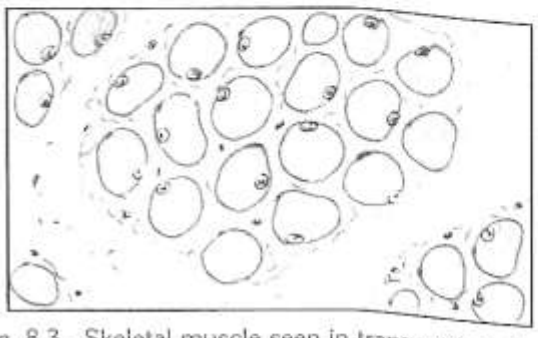

Fig. 8.3. Skeletal muscle seen in transverse section (drawing)

myofibrils. In transverse sections through muscle fibres, prepared by routine methods, the myofibrils often appear to be arranged in groups that are called the ***fields of Conheim***. The appearance is now known to be an artefact. The myofibrils are in fact distributed uniformly throughout the fibre.

The most striking feature of skeletal muscle fibres is the presence of transverse striations in them. After staining with haematoxylin the striations are seen as alternate dark and light bands that stretch across the muscle fibre. The dark bands are called ***A-bands***, while the light bands are called ***I-bands***. (As an aid to memory note that 'A' and 'I' correspond to the second letters in the words dark and light).

In good preparations (specially if the fibres are stretched) some further details can be made out. Running across the middle of each I-band there is a thin dark line called the ***Z-band***. The middle of the A-band is traversed by a lighter band, called the ***H-band*** (or ***H-zone***). Running through the centre of the H-band a thin dark line can be made out. This is the ***M-band***.

The various bands described are really present in myofibrils. They appear to run transversely across the whole muscle fibre because corresponding bands in adjoining myofibrils lie exactly in alignment with one another.

The part of a myofibril situated between two consecutive Z-bands is called a ***sarcomere***. The significance of the striations of myofibrils has to be understood in terms of their ultrastructure which is described on page 128.

In addition to myofibrils the sarcoplasm of a muscle fibre contains the usual cell organelles that tend to aggregate near the nuclei. Mitochondria are numerous. Substantial amounts of glycogen are also present. Glycogen provides energy for contraction of muscle.

Organisation of Muscle Fibres in Muscles

Within a muscle, the muscle fibres are arranged in the form of bundles or fasciculi. The number of fasciculi in a muscle, and the number of fibres in each fasciculus, are both highly variable. In small muscles concerned with fine movements (like those of the eyeball, or those of the vocal folds) the fasciculi are delicate and their number small. In large muscles (in which strength of contraction is the main consideration) fasciculi are coarse and numerous.

Muscles differ in the way their fasciculi are arranged. Some muscles (e.g., the sartorius) are strap-like, the fasciculi running the whole length of the muscle. Other muscles are fusiform, the

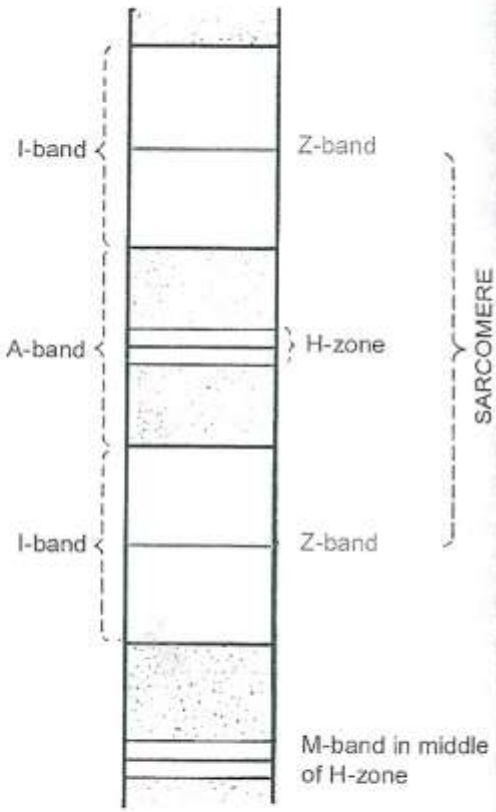

Fig. 8.4. Scheme to show the terminology of transverse bands in a myofibril. Note that the A-band is confined to one sarcomere, but the I-band is made up of parts of two sarcomeres that meet at the Z-band.

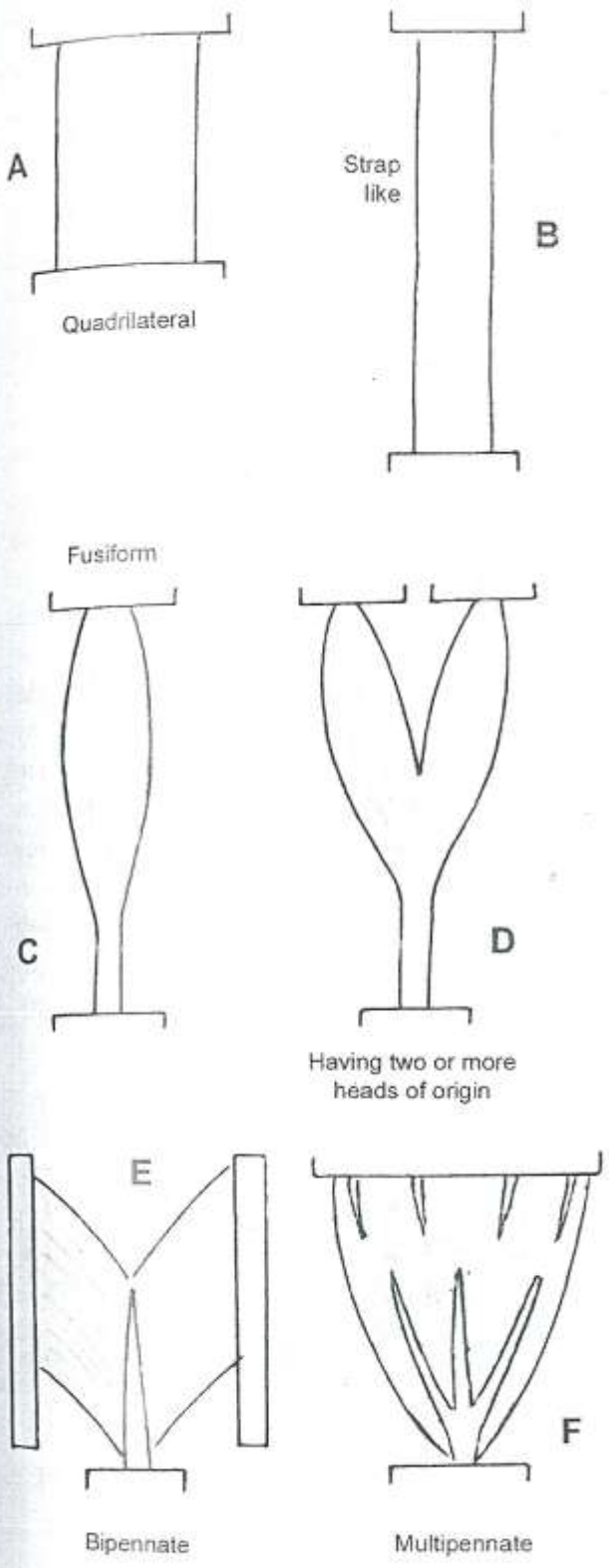

Fig. 8.5. Scheme to show some ways in which the fasciculi of a skeletal muscle may be arranged.

fasciculi being attached at one or both ends to tendons. In still other muscles, the fasciculi are much shorter than the total length of the muscle, and gain attachment to tendinous intersections within the muscle. Some variations in fascicular architecture are illustrated in Figs.8.5 A to F.

Variations in the fascicular architecture are to be correlated with the kind of movements performed by a muscle. A muscle fibre can shorten to about two-thirds of its full length. The total displacement that a muscle can produce is, therefore, proportional to the length of its fibres. In contrast the strength of contraction of a muscle depends on the number of fibres in a muscle (irrespective of their length). In some muscles a large number of short fasciculi are packed into a relatively small total volume (e.g., in a multipennate muscle like the deltoid: Fig. 8.5F). Such a muscle can exert much greater force than a long strap muscle having the same total volume.

Connective Tissue Framework of Muscles

Muscles are pervaded by a network of connective tissue fibres. This connective tissue supports muscle fibres and unites them to each other. Individual muscle fibres are surrounded by delicate connective tissue that is called the ***endomysium***. Individual fasciculi are surrounded by a stronger sheath of connective tissue called the ***perimysium***. Connective tissue that surrounds the entire muscle is called the ***epimysium***. At the junction of a muscle with a tendon the fibres of the endomysium, the perimysium and the epimysium become continuous with the fibres of the tendon.

Tendons

Tendons are composed of collagen fibres that run parallel to each other. The fibres are arranged in the form of bundles (Fig. 8.8). These bundles are united by areolar tissue, which contains numerous fibroblasts. In longitudinal sections

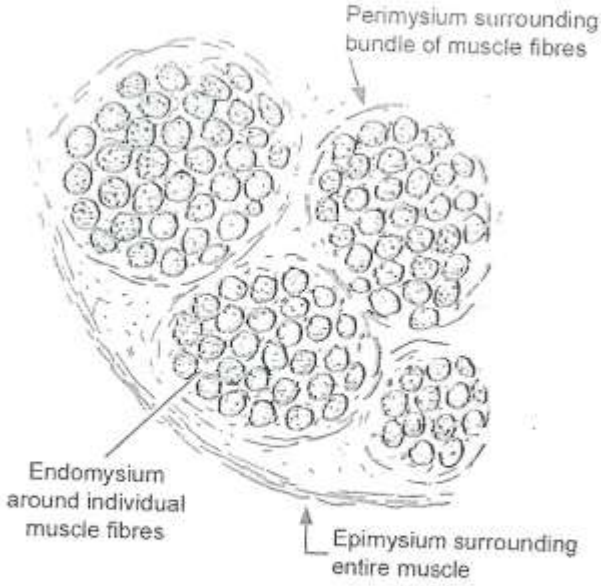

Fig. 8.6. Diagram to show the connective tissue present in relation to skeletal muscle (drawing).

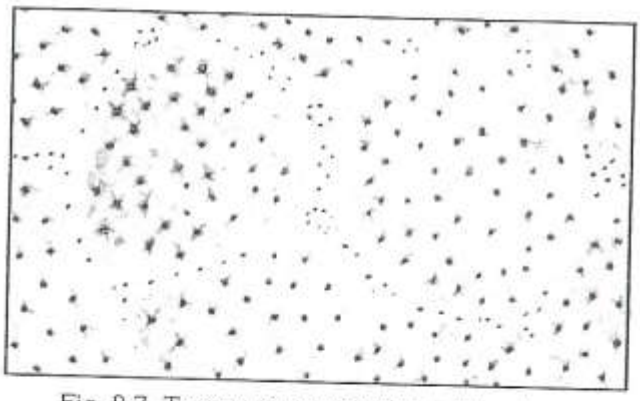

Fig. 8.7. Transverse section through tendon (drawing).

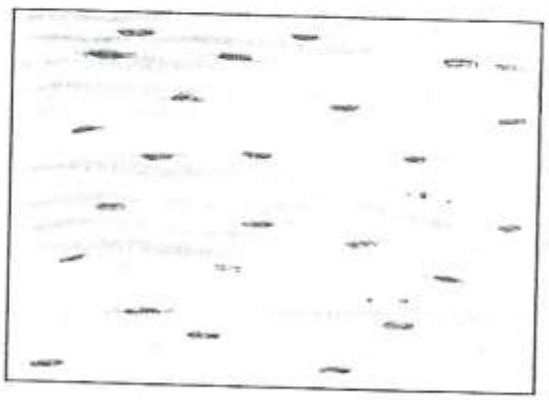

Fig. 8.8. Longitudinal section through tendon (drawing).

through a tendon the fibroblasts, and their nuclei, are seen to be elongated. In transverse sections, the fibroblasts are stellate. Tendons serve to concentrate the pull of a muscle on a relatively small area of bone. By curving around bony pulleys, or under retinacula, they allow alterations in the direction of pull. Tendons also allow the muscle mass to be placed at a convenient distance away from its site of action. (Imagine what would happen if there were no tendons in the fingers!).

Innervation of Skeletal Muscle

The nerve supplying a muscle enters it (along with the main blood vessels) at an area called the ***neurovascular hilus.*** This hilus is usually situated nearer the origin of the muscle than the insertion. After entering the muscle the nerve breaks up into many branches that run through the connective tissue of the perimysium and endomysium to reach each muscle fibre. The nerve fibres supplying skeletal muscle are axons arising from large neurons in the anterior (or ventral) grey columns of the spinal cord (or of corresponding nuclei in the brain stem).

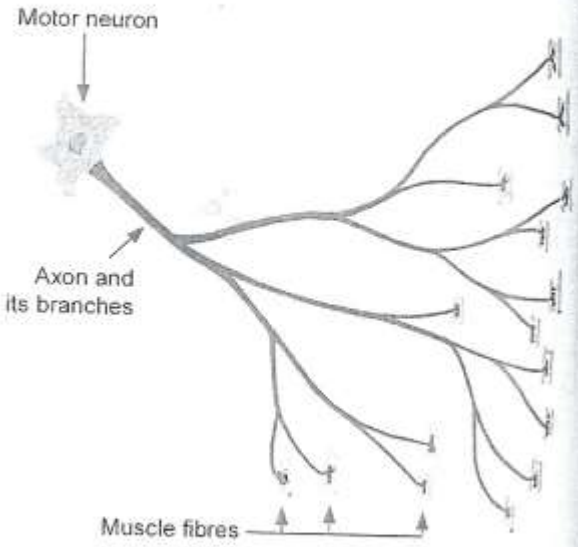

Fig. 8.9. Scheme to show the concept of a motor unit.

These *alpha-efferents* have a large diameter and are myelinated. Because of repeated branching of its axon, one anterior grey column neuron may supply many muscle fibres all of which contract when this neuron 'fires'. One anterior grey column neuron and the muscle fibres supplied by it constitute one ***motor unit.*** The number of muscle fibres in one motor unit is variable. The units are smaller where precise control of muscular action is required (as in ocular muscles), and much larger in limb muscles where force of contraction is more important. The strength with which a muscle contracts at a particular moment depends on the number of motor units that are activated.

The junction between a muscle fibre and the nerve terminal that supplies it is highly specialised and is called a ***motor end plate***. The structure of a motor end plate is described in Chapter 9.

Apart from the alpha efferents described above every muscle receives smaller myelinated *gamma-efferents* that arise from gamma neurons in the ventral grey column of the spinal cord. These fibres supply special muscle fibres that are present within sensory receptors called ***muscle spindles*** (see Chapter 9). These special muscle fibres are called ***intrafusal fibres***. Nerves to muscles also carry autonomic fibres that supply smooth muscle present in the walls of blood vessels.

Further Details About Skeletal Muscle

Origin of terms I-Band and A-Band

We have seen that the light and dark bands of myofibrils (or of muscle fibres) are designated I-bands and A-bands respectively. The letters 'I' and 'A' stand for the terms ***isotropic*** and ***anisotropic*** respectively. These terms refer to the way in which any material (e.g., a crystal) behaves with regard to the transmission of light through it. Some materials refract light equally in all directions: they are said to be isotropic. Other materials that do not refract light equally in different planes are anisotropic. These qualities depend on the arrangement of the elements making up the material. In the case of muscle fibres the precise reason for alternate bands being isotropic and anisotropic is not understood. The phenomenon is most probably due to peculiarities in arrangement of molecules within them.

Although striations can be made out in unstained material using ordinary light, they are much better seen through a microscope using polarised light.

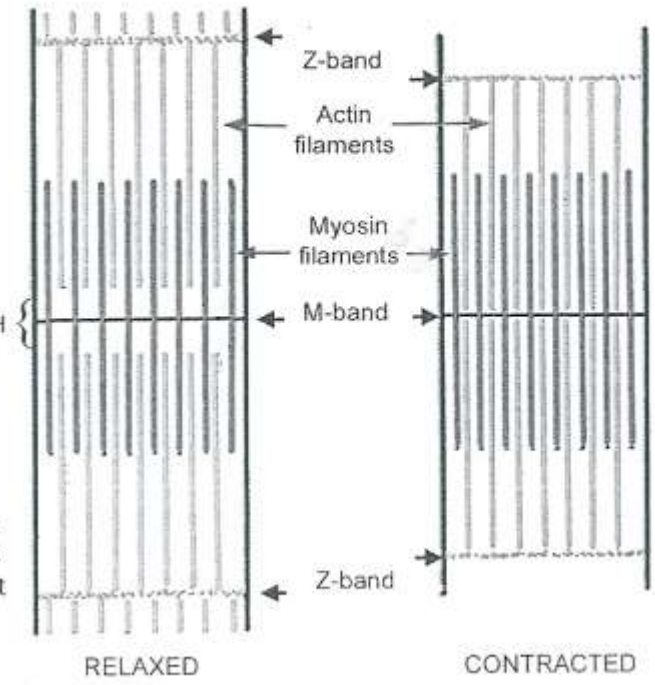

Fig. 8.10. Scheme to show how a myofibril shortens by sliding of actin filaments into the intervals between myosin filaments. Note that the width of the I-band becomes less, and that the H-zone disappears when the myofibril contracts.

Significance of letters Z, H, M

We have seen that the part of a myofibril between the two Z-bands is called a sarcomere. In other words a Z band is a plate lying between two sarcomeres. The letter 'Z' is from the German word ***zwischenschiebe*** (zwischen = between; schiebe = disc). The M-band is a plate lying in the middle of the sarcomere. The letter 'M' is from the German word ***mittleschiebe*** (mittle = middle). The H-band (or zone) is named after Hensen who first described it.

Ultrastructure of Striated Muscle

Each muscle fibre is covered by a plasma membrane that is called the ***sarcolemma***. The sarcolemma is covered on the outside by a ***basement membrane*** (also called the ***external lamina***) that establishes an intimate connection between the muscle fibre and the fibres (collagen, reticular) of the endomysium.

The cytoplasm (***sarcoplasm***) is permeated with myofibrils that push the elongated nuclei to a

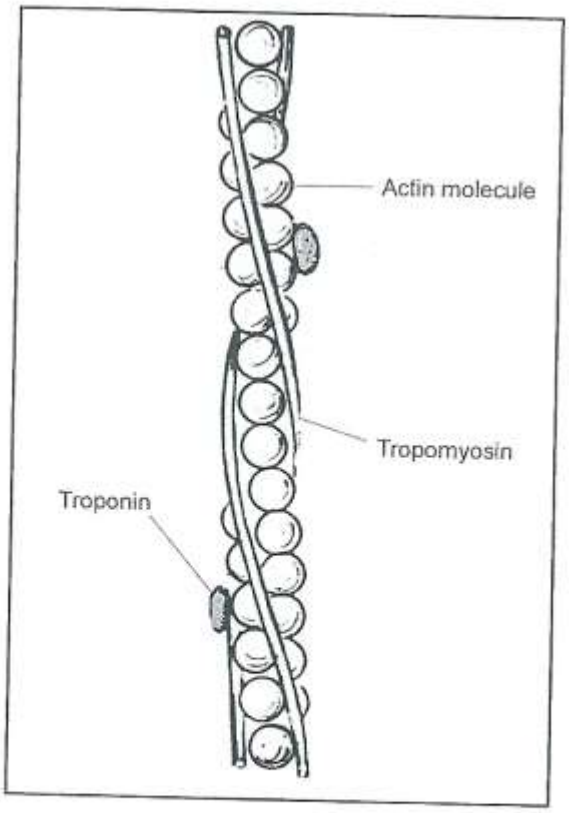

Fig. 8.11. Actin filament (F-actin) made up of globular molecules of G-actin.

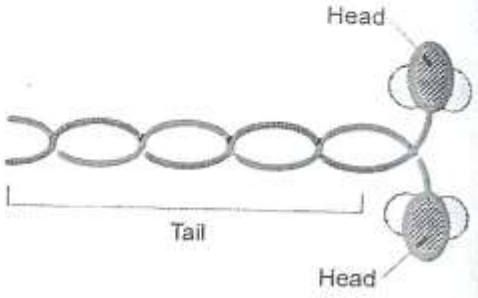

Fig. 8.12. Structure of a myosin molecule. Each molecule has two components (shown in red and green) each consisting of a head and a tail. The tails are coiled over each other. The parts shown in red or green are heavy myosin. Light myosin is shaded yellow.

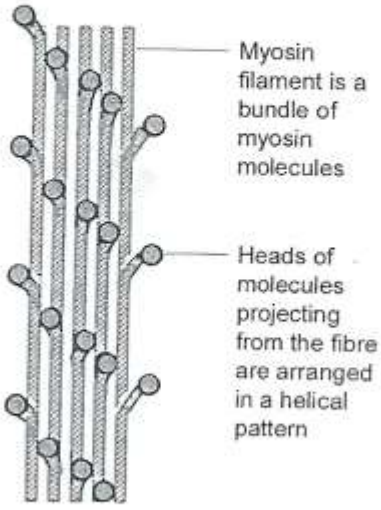

Fig. 8.13. Diagram to show a myosin filament made up of several molecules of myosin.

peripheral position. Between the myofibrils there is an elaborate system of membrane-lined tubes called the *sarcoplasmic reticulum*. Elongated mitochondria (*sarcosomes*) and clusters of glycogen are also scattered amongst the myofibrils. Perinuclear Golgi bodies, ribosomes, lysosomes, and lipid vacuoles are also present.

Structure of Myofibrils

When examined by EM each myofibril is seen to be made of fine myofilaments. These are of two types: ***actin*** and ***myosin***, made up of molecules of corresponding proteins. (Each myosin filament is about 12 nm in diameter, while an actin filament is about 8 nm in diameter. They are therefore referred to as thick and thin filaments respectively). The arrangement of actin and myosin filaments within a sarcomere is shown in Fig. 8.10. It will be seen that myosin filaments are confined to the A-band, the width of the band being equal to the length of the myosin filaments. The actin filaments are attached at one end to the Z-band. From here they pass through the I-band and extend into the 'outer' parts of the A-band, where they interdigitate with the myosin filaments. Note that the I-band is made up of actin filaments alone. The H-band represents the part of the A-band into which actin filaments do not extend. The Z-band is really a complicated network at which the actin filaments of adjoining sarcomeres meet. The M-band is produced by fine interconnections between adjacent myosin filaments.

In an uncontracted myofibril, overlap between actin and myosin filaments is minimal. During contraction the fibril shortens by sliding in of actin filaments more and more into the intervals between the myosin filaments. As a result the width of the I-band decreases, but that of the A-band is unchanged. The H-bands are obliterated in a contracted fibril.

To understand the mechanism by which actin filaments 'slide' into the A-band, it is necessary to examine the structure of actin and myosin filaments in greater detail.

Each ***actin filament*** is really composed of two subfilaments that are twisted round each other (Fig. 8.11). Each subfilament is a chain of globular (rounded) molecules. These globular molecules are G-actin, and the chain formed by them is designated as ***f-actin***. Each actin filament has a head end (that extends into the A-band) and a tail end that is anchored to the Z-line (through a protein called α-actinin). The filament also contains two other proteins called ***tropomyosin*** and ***troponin***. Tropomyosin is in the form of a long fibre that winds around actin and stabilises it. Troponin is a complex made up of several fractions. These complexes are arranged regularly over the actin fibre and represent sites at which myosin binds to actin.

Each ***myosin filament*** is made up of a large number of myosin molecules. Each molecule is made up of two units, each unit having a head and a tail (Fig. 8.12). The tails are coiled over each other. A myosin filament is a 'bundle' of the tails of such molecules. The heads project outwards from the bundle as projections of the myosin filament. The projecting heads are arranged in a regular helical manner.

Because of the manner in which it is formed each myosin fibril can be said to have a head end and a tail end. The tail end is attached to the M-line.

Movement is produced by interaction of actin and myosin filaments as follows. Myosin filaments establish bonds with adjoining actin filaments. After making a bond a head probably

'bends' dragging the actin filament with it. The original bond is now broken, the head unbends, and establishes another bond with the next part of the actin filament. These bonds are made and unmade in rapid succession dragging actin filaments into the intervals between the myosin filaments. This is the probable mechanism for shortening of myofibrils, and hence for the contraction of muscle.

It will be obvious that for successful operation of such a system the actin and myosin filaments must be arranged in a precise geometrical fashion: and this is indeed the case (Fig.8.14). This precision of alignment is achieved through ***accessory proteins*** that link the different components.

The energy for repeated binding and release of the heads of myosin molecules to actin is derived from hydrolysis of ATP. ATP binds to the myosin head. When the head comes in contact with actin ATP is hydrolysed to form ADP and phosphate. This leads to firm binding of the head to actin. After a short interval ADP is released by the head, which now separates from actin. Fresh ATP binds to the head and the cycle is repeated.

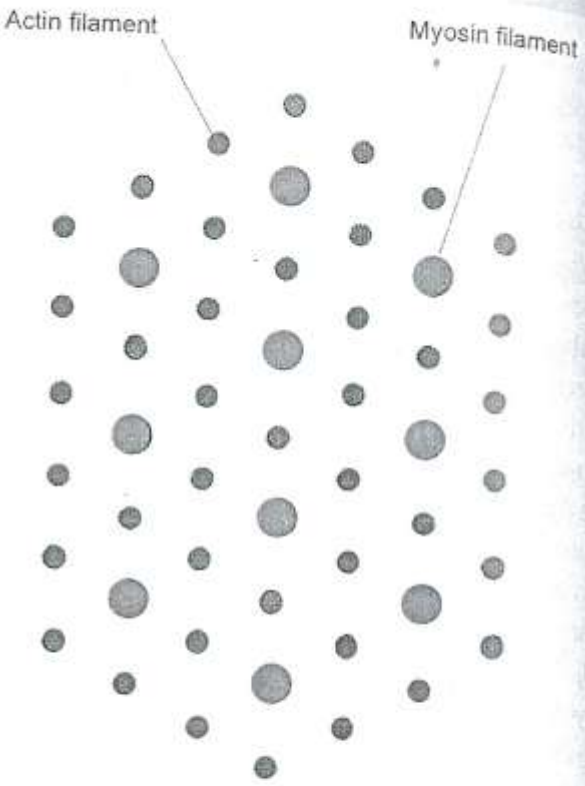

Fig. 8.14. Schematic T.S. through A-band to show the regular geometric arrangement of actin and myosin filaments. Myosin filaments are arranged in triangular arrays. Each myosin filament is surrounded by six actin filaments.

Other Proteins present in muscle

Several proteins other than actin and myosin are present in muscle. Some of them are as follows.

1. ***Actinin*** is present in the region of Z discs. It binds the tail ends of actin filaments to this disc.

2. ***Myomesin*** is present in the region of the M disc. It binds the tail ends of myosin filaments to this disc.

3. ***Titin*** links the head ends of myosin filaments to the Z disc. This is a long and elastic protein that can lengthen and shorten as required. It keeps the myosin filament in proper alignment.

4. ***Desmin*** is present in intermediate filaments of the cytoskeleton. It links myofibrils to each other, and also to the cell membrane.

Some other proteins are also present.

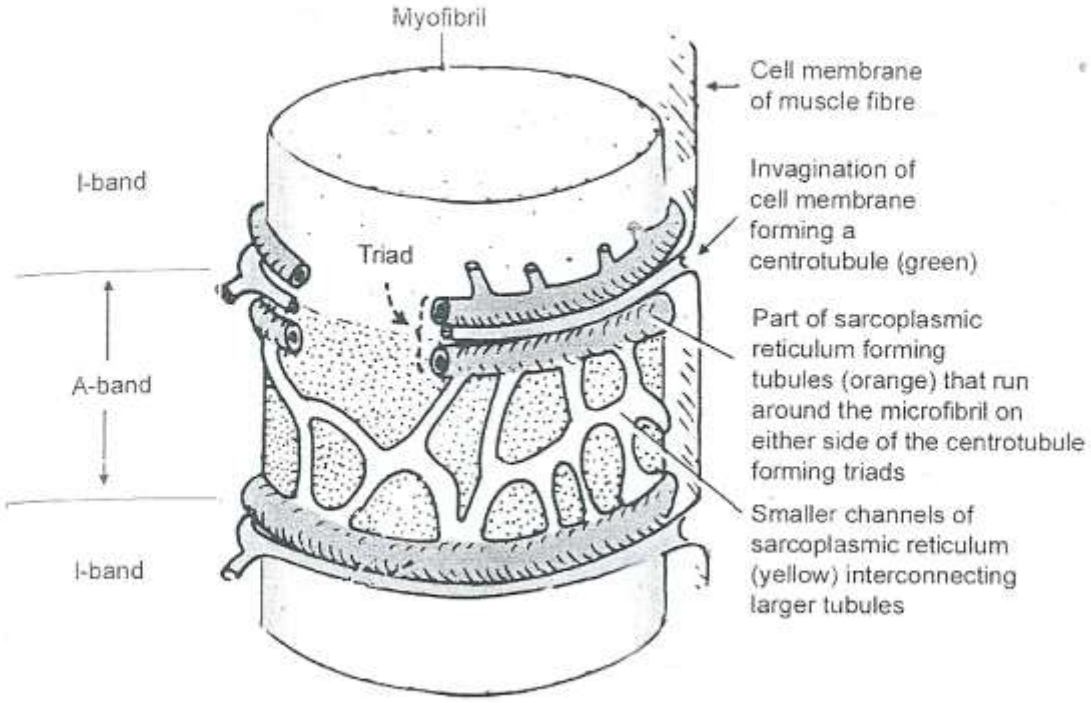

Fig. 8.15. Diagram to show the relationship of the sarcoplasmic reticulum, and the T-tubes to a myofibril.

Each muscle fibre contains a cytoskeleton. The fibres of the cytoskeleton are linked to actin fibres. The cytoskeleton is also linked to the external lamina through glycoproteins present in the cell membrane. Forces generated within the fibre are thus transmitted to the external lamina. The external lamina is in turn attached to connective tissue fibres around the muscle fibre. A number of proteins are responsible for these linkages. Genetic defects in these proteins can result in abnormalities in muscle (muscle dystrophy).

Sarcoplasmic Reticulum

In the intervals between myofibrils, the sarcoplasm contains an elaborate system of tubules called the sarcoplasmic reticulum (Fig. 8.15). The larger elements of this reticulum run in planes at right angles to the long axes of the myofibrils, and form rings around each myofibril. At the level of every junction between an A and I band the myofibril is encircled by a set of three closely connected tubules that constitute a ***muscle triad***. For purposes of description each such triad can be said to be composed of an upper, a middle, and a lower tubule (Fig.8.15). The upper and lower tubules of the triad are connected to the tubules of adjoining triads through a network of smaller tubules. There is one such network opposite each A-band, and another opposite each I-band. These networks, along with the upper and lower tubules of the triad, constitute the sarcoplasmic reticulum. This reticulum is a closed system of tubes.

The middle tube of the triad is an entity independent of the sarcoplasmic reticulum. It is called a ***centrotubule*** and belongs to what is called the ***T-system*** of membranes. The

centrotubules are really formed by invagination of the sarcolemma into the sarcoplasm. Their lumina are, therefore, in communication with the exterior of the muscle fibre. As already noted the centrotubules permeate the entire muscle fibre as they form networks around myofibrils as part of the muscle triads.

Contraction of muscle is dependent on release of calcium ions into myofibrils. In a relaxed muscle these ions are strongly bound to the membranes of the sarcoplasmic reticulum. When a nerve stimulus reaches a motor end plate the sarcolemma is depolarised. The wave of depolarisation is transmitted to the interior of the muscle fibre through the centrotubules. As a result of this wave calcium ions are released from the sarcoplasmic reticulum into the myofibrils causing their contraction.

Red (or Slow Twitch) & White (or Fast Twitch) Muscle

It has been known since long that some skeletal muscle fibres are reddish in colour while others are whitish. As compared to white fibres the contraction of red fibres is relatively slow. Hence red fibres are also called ***slow twitch fibres***, or ***type I fibres***; while white fibres are also called ***fast twitch fibres*** or ***type II fibres***.

The colour of red fibres is due to the presence (in the sarcoplasm) of a pigment called ***myoglobin***. This pigment is similar (but not identical with) haemoglobin. It is present also in white fibres, but in much lesser quantity.

In addition to colour and speed of contraction there are several other differences between red and white fibres. In comparison to white fibres red fibres differ as follows.

Red fibres are narrower than white fibres. Relative to the volume of the myofibrils the sarcoplasm is more abundant. Probably because of this fact the myofibrils, and striations, are less well defined; and the nuclei are not always at the periphery, but may extend deeper into the fibre. Mitochondria are more numerous in red fibres, but the sarcoplasmic reticulum is less extensive. The sarcoplasm contains more glycogen. The capillary bed around red fibres is richer than around white fibres. Differences have also been described in enzyme systems and the respiratory mechanisms in the two types of fibres. Fibres intermediate between red and white fibres have also been described.

In some animals complete muscles may consist exclusively of red or white fibres, but in most mammals, including man, muscles contain an admixture of both types. Although red fibres contract slowly their contraction is more sustained, and they fatigue less easily. They predominate in the so called postural muscles (which have to remain contracted over long periods), while white fibres predominate in muscles responsible for sharp active movements.

Type II (white) fibres may be divided into type IIA and type IIB, the two types differing in their enzyme content, and in the chemical nature of their myosin molecules.

Blood Vessels and Lymphatics of Skeletal Muscle

Skeletal muscle is richly supplied with blood vessels. The main artery to the muscle enters it at the neurovascular hilus. Several other arteries may enter the muscle at its ends or at other places along its length. The arteries form a plexus in the epimysium and in the perimysium, and end in a network of capillaries that surrounds each muscle fibre. This network is richer in red muscle than in white muscle.

Veins leaving the muscle accompany the arteries. A lymphatic plexus extends into the epimysium and the perimysium, but not into the endomysium. The innervation of skeletal muscle has been described on page 126.

Cardiac Muscle

The structure of cardiac muscle has many similarities to that of skeletal muscle; but there are important differences as well.

Similarities between Cardiac & Skeletal Muscle

These are as follows. Like skeletal muscle, cardiac muscle is made up of elongated 'fibres' within which there are numerous myofibrils. The myofibrils (and, therefore, the fibres) show transverse striations similar to those of skeletal muscle. A, I, Z and H bands can be made out in the striations. The connective tissue framework, and the capillary network around cardiac muscle fibres are similar to those in skeletal muscle.

With the EM it is seen that myofibrils of cardiac muscle have the same structure as those of skeletal muscle and are made up of actin and myosin filaments. A sarcoplasmic reticulum, T-system of centrotubules, numerous mitochondria and other organelles are present.

Differences between Cardiac & Skeletal Muscle

These are as follows.

1. The fibres of cardiac muscle do not run in strict parallel formation, but branch and anastomose with other fibres to form a network.

2. Each fibre of cardiac muscle is not a multinucleated syncytium as in skeletal muscle, but is a chain of cardiac muscle cells (or ***cardiac myocytes***) each having its own nucleus. Each myocyte is about 80 μm long and about 15 μm broad.

3. The nucleus of each myocyte is located centrally (and not peripherally as in skeletal muscle).

4. The sarcoplasm of cardiac myocytes is abundant and contains numerous large mitochondria. The myofibrils are relatively few. At places, the myofibrils merge with each other. As a result of these factors, the myofibrils and striations of cardiac muscle are not as distinct as those of skeletal muscle. In this respect cardiac muscle is closer to the red variety of skeletal muscle than to the white variety. Other similarities with red muscle are the presence of significant amounts of glycogen and of myoglobin, and the rich density of the capillary network around the fibres.

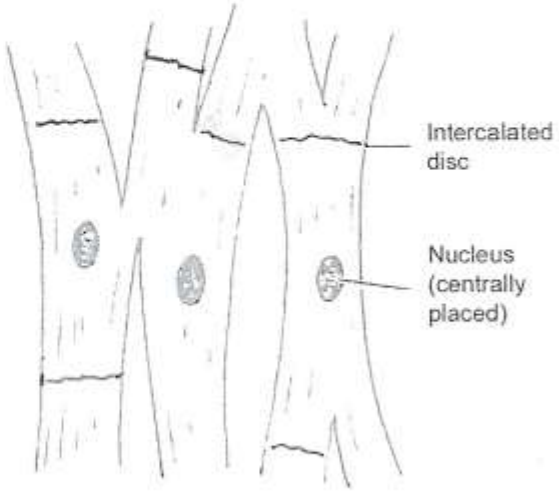

Fig. 8.16. Cardiac muscle (diagrammatic).

With the EM it is seen that the sarcoplasmic reticulum is much less prominent than in skeletal muscle. The centrotubules of the T-system lie opposite the Z-bands (and not at the junctions of A and I-bands as in skeletal muscle). The tubules are much wider than in skeletal muscle. Typical triads are not present. They are often replaced by ***dyads*** having one T-tube and one tube of the sarcoplasmic reticulum.

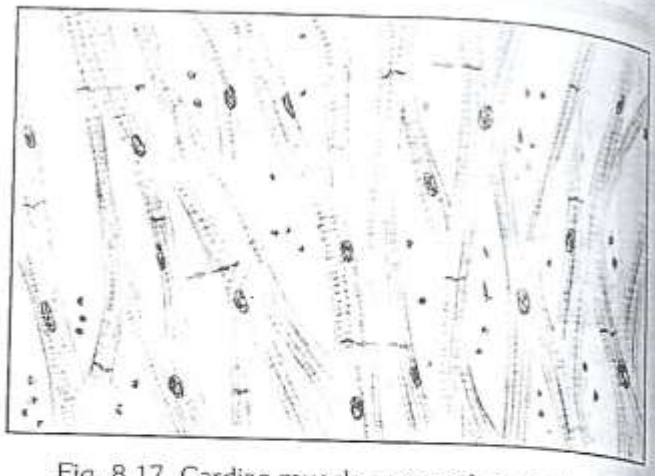

Fig. 8.17. Cardiac muscle as seen in a section (drawing).

5. With the light microscope the junctions between adjoining cardiac myocytes are seen as dark staining transverse lines running across the muscle fibre. These lines are called ***intercalated discs***. Sometimes these discs do not run straight across the fibres, but are broken into a number of 'steps' (Fig. 8.17). The discs always lie opposite the I-bands.

With the EM it is seen that the intercalated discs are formed by cell membranes of adjacent myocytes, and by a layer of particularly dense cytoplasm present next to the cell membrane. The ends of actin filaments are embedded in this dense cytoplasm. The cell membranes of adjoining myocytes are connected by numerous desmosomes, gap junctions, and tight junctions. Desmosomes link intermediate filaments present in the cytoskeleton of adjacent cells. Actin filaments of the cells end in relation to tight junctions. Gap junctions allow electrical continuity between adjacent myocytes, and thus convert the cardiac muscle into a ***physiological syncytium***.

6. Cardiac muscle is involuntary and is innervated by autonomic fibres (in contrast to skeletal muscle that is innervated by cerebrospinal nerves). Nerve endings terminate near the cardiac myocytes, but motor end plates are not seen.

Isolated cardiac myocytes contract spontaneously in a rhythmic manner. In the intact heart the rhythm of contraction is determined by a pace maker located in the sinuatrial node. From here the impulse spreads to the entire heart through a conducting system made up of a special kind of cardiac muscle. From the above it will be appreciated that a nerve supply is not necessary for contraction of cardiac muscle. Nervous influences do, however, influence the strength and rate of contraction of the heart.

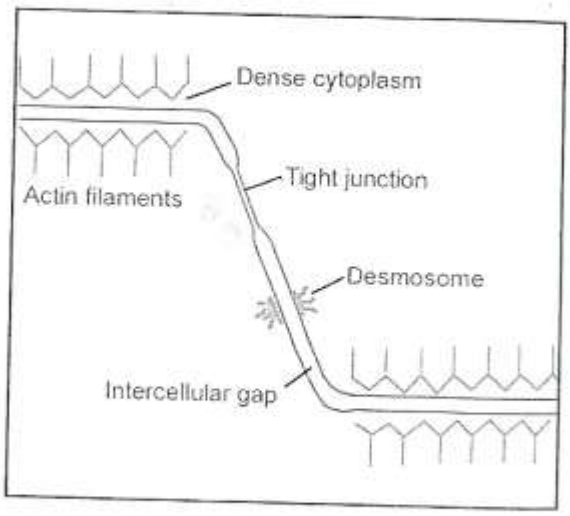

Fig. 8.18. Diagram to show the EM structure of part of an intercalated disc.

Smooth Muscle

Basic Facts About Smooth Muscle

Smooth muscle (also called ***non-striated, involuntary*** or ***plain muscle***) is made up of long spindle shaped cells (myocytes) having a broad central part and tapering ends. The nucleus, which is oval or elongated, lies in the central part of the cell. The length of smooth muscle cells (often called fibres) is highly variable (15 μm to 500 μm).

With the light microscope the sarcoplasm appears to have indistinct longitudinal striations, but there are no transverse striations.

Fig. 8.19. Smooth muscle cells (diagrammatic)

Smooth muscle cells are usually aggregated to form bundles, or fasciculi, that are further aggregated to form layers of variable thickness. In such a layer the cells are so arranged that the thick central part of one cell is opposite the thin tapering ends of adjoining cells. Aggregations of smooth muscle cells into fasciculi and layers is facilitated by the fact that each myocyte is surrounded by a network of delicate fibres (collagen, reticular, elastic) that holds the myocytes together. The fibres between individual myocytes become continuous with the more abundant connective tissue that separates fasciculi or layers of smooth muscle.

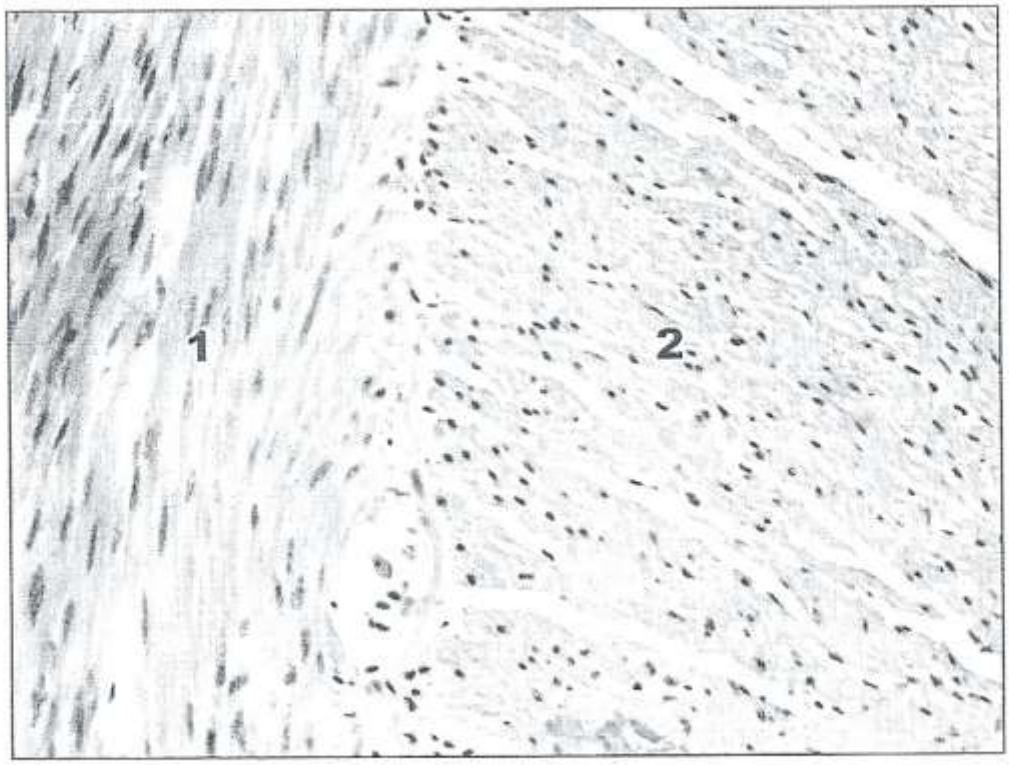

Fig. 8.20. Smooth muscle as seen in a section (photomicrograph). 1-L.S. 2-T.S.

Distribution of Smooth Muscle

(a) Smooth muscle is seen most typically in the walls of hollow viscera including the stomach, the intestines, the urinary bladder and the uterus.

(b) It is present in the walls of several structures that are in the form of narrow tubes e.g., arteries, veins, bronchi, ureters, deferent ducts, uterine tubes, and the ducts of several glands.

(c) The muscles that constrict and dilate the pupil are made up of smooth muscle.

(d) Some smooth muscle is present in the orbit (orbitalis); in the upper eyelid (Muller's muscle); in the prostate; in the skin of the scrotum (Dartos muscle). In the skin delicate bundles of smooth muscle are present in relation to hair follicles. These bundles are called the ***arrector pili*** muscles (Chapter 12).

Variations in Arrangement of Smooth Muscle

Smooth muscle fibres may be arranged in a variety of ways depending on functional requirements.

(a) In some organs (e.g., the gut) smooth muscle is arranged in the form of two distinct layers: an inner circular and an outer longitudinal. Within each layer the fasciculi lie parallel to each other. Such an arrangement allows peristaltic movements to take place for propulsion of contents along the tube.

In some organs (e.g., the ureter) the arrangement of layers may be reversed, the longitudinal layer being internal to the circular one. In yet other situations there may be three layers: inner and outer longitudinal with a circular layer in between.

(b) In some regions (e.g., urinary bladder, uterus) the smooth muscle is arranged in layers, but the layers are not distinctly demarcated from each other. Even within layers the fasciculi tend to run in various directions and may form a network. In these organs contraction of muscle reduces the size of the lumen of the organ and pushes out its contents.

(c) In some tubes (e.g., the bile duct) a thick layer of circular muscle may surround a segment of the tube forming a ***sphincter***. Contraction of the sphincter occludes the tube.

(d) In the skin, and in some other situations, smooth muscle occurs in the form of narrow bands.

Innervation of Smooth Muscle

Smooth muscle is innervated by autonomic nerves, both sympathetic and parasympathetic. The two have opposite effects. For example, in the iris, parasympathetic stimulation causes constriction of the pupil, and sympathetic stimulation causes dilatation. It may be noted that sympathetic or parasympathetic nerves may cause contraction of muscle at some sites, and relaxation at other sites.

For further details see below.

Blood vessels & Lymphatics of Smooth Muscle

Blood vessels and lymphatics are present in smooth muscle, but the density of blood vessels is much less than in skeletal muscle (in keeping with much less activity).

Some Further Facts About Smooth Muscle

Ultrastructure

Each smooth muscle cell is bounded by a plasma membrane. Outside the plasma membrane there is an external lamina to which the plasma membrane is adherent. Connective tissue fibres are attached to the lamina (through special proteins). Adjacent smooth muscle cells communicate through gap junctions. The longitudinal striations (see with the light microscope) are due to the presence of delicate myofilaments. These myofilaments are composed mainly of the proteins actin and myosin, but these do not have the highly ordered arrangement seen in striated muscle. Apart from myofibrils the sarcoplasm also contains mitochondria (which provide energy), a Golgi complex, some granular endoplasmic reticulum, free ribosomes, and intermediate filaments. A sarcoplasmic reticulum, similar to that in skeletal muscle, is present, but is not as developed. Numerous invaginations (caveolae) resembling endocytic vesicles are seen near the surface of each myocyte, but no endocytosis occurs here.

The mechanism of contraction of smooth muscle is different from that of skeletal muscle as follows.

1. The myosin is chemically different from that in skeletal muscle. It binds to actin only if its light chain is phosphorylated. This phosphorylation of myosin is necessary for contraction of smooth muscle.
2. The actin filaments are also different from those in skeletal muscle. Troponin is not present.
3. As compared to skeletal muscle, smooth muscle needs very little ATP for contraction.
4. The mechanisms regulating the flow of calcium ions into smooth muscle are different from those for skeletal muscle. Caveolae present on the surface of smooth muscle cells play a role in this process.
5. Actin and myosin form bundles that are attached at both ends to the points on the cell membrane called anchoring points (or focal densities). When the muscle contracts these points are drawn closer to each other. This converts an elongated smooth muscle cell in one that is oval (Fig. 8.21).

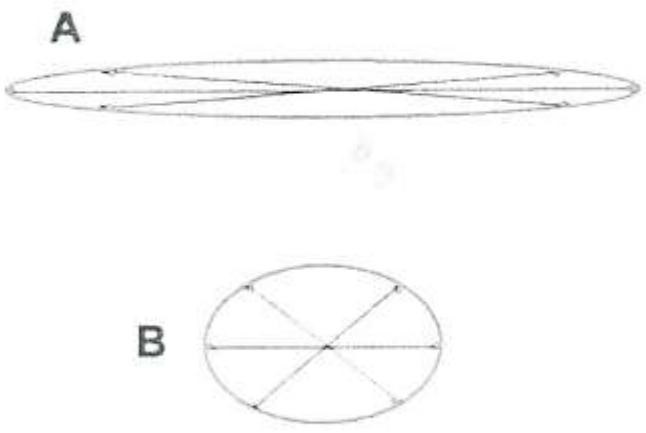

Fig. 8.21. Diagram to show contractile fibres in smooth muscle stretching between anchoring points on the cell membrane. The cell is shown in the relaxed state in A, and in the contracted state in B.

Further Details of Innervation

The relationship of nerve terminals to smooth muscle cells is much less intimate than that in skeletal muscle. Nerve terminals end in direct relation to only some myocytes. It is believed that impulses travel from one myocyte to another through areas where the plasma membranes of adjacent myocytes actually fuse forming a nexus. Gap junctions connect adjacent myocytes

and facilitate excitation of one myocyte by another. This arrangement is to correlated with the fact that, as compared to skeletal muscle, smooth muscle contracts rather slowly. The contraction is, however, more sustained. Afferent nerve fibres are also to be seen in smooth muscle.

Multi-unit and Unitary

Smooth Muscle

From the point of view of its nerve supply smooth muscle is divided into two main types: multi-unit and unitary.

In multi-unit muscle nerve fibres establish direct contact with several myocytes (but not with all of them). This kind of muscle contracts when an appropriate nerve stimulus reaches it i.e., contraction is neurogenic. Smooth muscle of this kind is present in the iris, in large arteries, and in the ductus deferens.

In contrast to multi-unit muscle, unitary smooth muscle has its own rhythmic contractility that is independent of a nerve supply. The rate of contraction may be determined by pace maker regions present within the muscle. Contraction of this type of muscle can also be stimulated by stretching. In unitary smooth muscle the nerve endings are less numerous than in multi-unit muscle. The role of the nerves is to increase or decrease the rate of rhythmic contraction. Smooth muscle of this kind is present in the stomach, the intestines, the uterus and the ureter.

Intermediate forms of smooth muscle between the two types described above are also present.

Some other functions of Smooth Muscle

It has been shown that in some ways smooth muscle cells resemble fibroblasts. Myocytes can produce collagen, elastic fibres, and other components of connective tissue matrix. The connective tissue matrix seen in smooth muscle is believed to be produced by smooth muscle cells themselves, fibroblasts being usually missing.

OTHER CONTRACTILE CELLS

Apart from muscle some other cells show the presence of contractile proteins (actin and myosin). These are as follows.

Myoepithelial Cells

In relation to some glands contractile cells are present in close relation to secretory elements. Such cells are called ***myoepitheliocytes*** (or ***myoepithelial cells***). They help to squeeze secretions out of secreting elements. Myoepithelial cells may be ***stellate***, forming baskets around acini, or may be ***fusiform***.

Myoepitheliocytes are seen in salivary glands, the mammary glands, and sweat glands. These cells are of ectodermal origin. With the EM they are seen to contain actin and myosin filaments. They can be localised histochemically, because they contain the protein ***desmin*** that is specific to muscle. Myoepithelial cells are innervated by autonomic nerves.

Myofibroblasts

These are described on page 66.

Pericytes

See page 182

SOME CLINICAL CORRELATIONS OF MUSCLE

1. All varieties of muscle can hypertrophy when exposed to greater stress. Hypertrophy takes place by enlargement of existing fibres, and not by formation of new fibres. Skeletal muscle hypertrophies with exercise. Cardiac muscle hypertrophies if the load on a chamber of the heart is increased for any reason. An example is the hypertrophy of muscle in the wall of the left ventricle in hypertension. Hypertrophy of smooth muscle is seen most typically in the uterus where myocytes may increase from a length of about 15 to 20 μm at the beginning of pregnancy to as much as 500 μm towards the end of pregnancy.

2. Smooth muscle and cardiac muscle have very little capacity for regeneration. Any defects produced by injury or disease are usually repaired by formation of fibrous tissue.

Skeletal muscle fibres can undergo some degree of regeneration. They cannot divide to form new fibres. However, ***satellite cells*** present in relation to them (just deep to the external lamina) can give rise to new muscle fibres. Satellite cells are regarded as persisting myoblasts. When large segments of a muscle are destroyed the gap is filled in by fibrous tissue.

3. Excessive activity of smooth muscle is responsible for many symptoms. Constriction of bronchi leads to asthma. Spasm of smooth muscle can give rise to severe pain (colic) that may originate in the intestines (intestinal colic), ureter (renal colic), or bile duct (biliary colic). These symptoms can be relieved by drugs that cause relaxation of smooth muscle.

4. Proliferation of myofibroblasts is seen in tissue repair, and is associated with some diseases including cirrhosis of the liver, fibrosis of the lung, and atheroma of arteries.

5. Some diseases of muscle (referred to as muscular dystrophy) are caused by genetic defects in proteins that link fibres of the cytoskeleton to the external lamina. One such protein is dystrophin, and its absence is associated with a disease called Duchenne muscular dystrophy.