Neural Science for Engineers
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Lecture - 43
The Human Balance System

So, in a previous session we discussed about the hearing mechanisms and how hearing signal, say sound signals are converted into electrical signals and processed at various parts of the hearing mechanism and the ultimate destine to the auditory cortex. The vestibular system is discussed in parallel with hearing, primarily because of the closed proximity of the entity, that is the first reason.

Vestibular system has already introduced in the hearing session. It is the set of sensors which are responsible for balance, maintenance of balance. There are several mechanisms by which balance is maintained. Now, one of the important systems is vestibular, but by no means is it an exclusive method of balance. Now, conventionally the three mechanisms of balance are; one is visual in which you are able to align yourself to the horizontal.

You also have the sensory system by which you perceive joint sense from each of your joints which gives you the understanding, the brain understands that what posture you are in at various joints. And thereby, it can compute and calculate your net position. The vestibular system incidentally computes the net balance state of your head, it is basically because the sensors are located in your head.

And, by inference judges as to what is the position, what is the movement, what is the amount of rotation. So, how this is carried about is what I have tried to highlight in this system.

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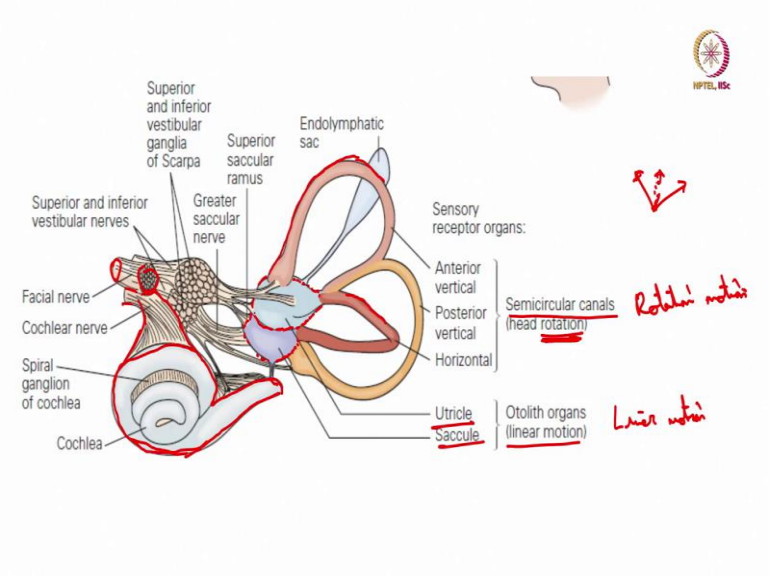

So, as in the in continuation with the previous discussion I will I have already shown you how it looks like on imaging and how these things are so closely placed with each other. It is a bit difficult to understand these things in imaging because, these are three-dimensional structures. So, I have to make use of diagrams to explain these things, please do bear me bear with me for that. Now, we have so far discussed this entity which is the cochlea and how the cochlea mediates hearing.

So, far we have been discussing about this part of the know which is the 8th nerve and the 8th nerve, if you recollect it goes out through the goes back into the skull through the internal acoustic meatus. Internal acoustic meatus has two other separate entities: one is the facial nerve, and the other is the vestibular nerve. Now, the vestibule is in vestibule is in close proximity as I told you with the cochlea. And there are several different components of that, the most obvious and obvious component is this circular rings.

So, there are three sets of circular rings, and these three rings are actually perpendicular to each other. So, that is the kind of orientation which is there for each of these three canals.

So, they are called as the semicircular canals, and they are primarily concerned with sensing rotation. Now, along with these canals are these smaller entities over here which are called utricle, this one is the utricle, and this is the saccule. So, utricle and saccule are with for linear motion, so linear movement motion and rotational motion. So, how this is

transduced we will see subsequently. So, each ear has one set of this apparatus and that is how it would be.

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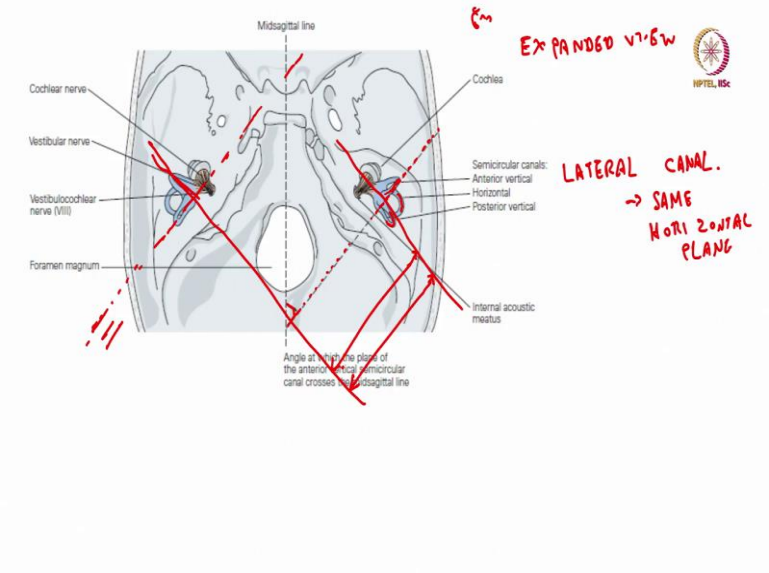

So, you have both of these are situated within the petrous bone, this is an expanded view, in a sense not in proportion. So, the superior semicircular canal, which is this one, lateral semicircular canal which is this one and the posterior semicircular canal which is this one. So, they are as I told you perpendicular to each other and the direction of these are quite specific.

So, the anterior semicircular canal, the anterior most, anterior is in front, anterior most semicircular canal is in this plane ok. Now, this anterior canal would be parallel to the posterior canal plane.

So, the lateral semicircular canals are in the same plane, in the sense that they are in the same horizontal plane. The other two that is the anterior is corresponding is parallel to the posterior canal and this anterior canal is parallel to this posterior canal; so, that is the orientation. So, there are three of them in three-dimensional space and the horizontal is just about at this plane.

So, the horizontal is not exactly in line with the with your face being looking straight ahead its slightly at a tilt and the other three, other two are in perpendicular location. So, what is so, they form pairs. So, anterior of one side forms a pair with the posterior of the

opposite side and vice versa, posterior of the same side forms a pair with the anterior of the other side.

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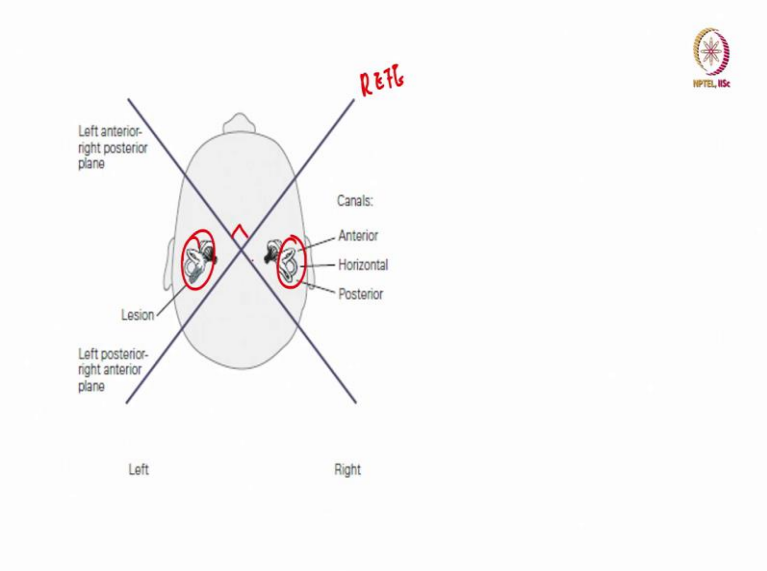

So, basically there are these planes which are the reference planes and the data from each individual semicircular canal set is used to compute movements within these two or two perpendicular planes.

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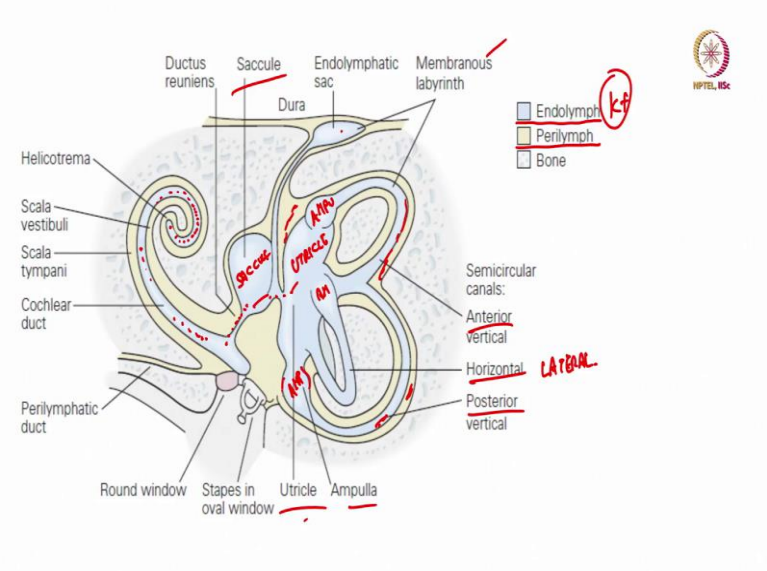

So, that is the; that is the orientation with reference to the head. So, how they are situated on both sides and how they mirror each other on either side, and they are

complementary. So, complementary in the sense that they are mapped such that two sets of canals give a particular data on from either side. Now, why either side? Because we are bilaterally symmetrical organisms and you need to take data and the head as such is fixed on the neck which you can you have about 2 degrees of freedom on your neck.

And that is the reason why you have those kinds of arrangements. Hawick said that it should be remember that these are some of the most primitive kinds of sensor systems which are there. The textbook actually says that is nearly about 500 million years old because, several kinds of lower organisms have very similar mechanisms of maintaining balance and balance is very important for most organisms.

Because they need to be upright and upright as in for the organism and it has a lot of bearing on hosting while surviving in hostile environments. So, the internal mechanism is somewhat like this, it is similar to what we saw. So, there is the same endolymph and perilymph which is there within the within these cavities, the cavities are similar like this. So, the this is the cochlear endolymph.

So, the cochlear endolymph actually continues through the cochlear duct into the saccule and from the saccule it also goes into something called endolymphatic sac which is not actually relevant for a current discussion. But so, saccule then there is utricle then so, the ampulla there are three ampullas here and each of these semicircular canals this is a planar representation. So, that is why you cannot make out the; make out the orientation on this diagram.

So, the endolymphatic endolymph is causing as a single entity through these diverse mechanisms, do remember that this is the same this is a closed system. See there is another thing called as a perilymph which is outside. The perilymph in the cochlea is connected to hearing, the hearing transaction mechanism. Here it is not connected to the hearing transaction mechanism, but it is the whole the system is based in the same fluid.

Now, endolymph is potassium rich; so, the mode of dominant ion for computation is potassium as opposed to sodium, which is the ion in most neurological, other neurological systems; maybe has something to do with the evolutionary component of this. So, these are the parts utricle, ampulla, the membranous labyrinth is the inside part of it and saccule and utricle. So, ampulla is the is this dilated part which is there for each one of these semicircular canals.

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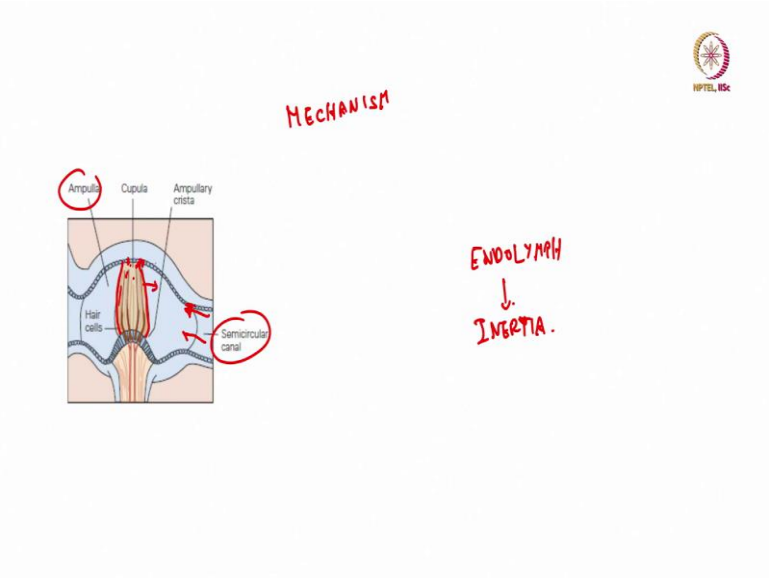

So, that is how the arrangement is, each of this mechanism of action is similar in all these cases whether it be the semicircular canal or the uterical and the cycle. There are some anatomical differences between the kind of arrangement which is there between the cells and some other stuff which I am not actually interested, meaning not explaining.

So, this is a diagram in the ampulla, and this is a semicircular canal. So, within the ampulla is a structure called as a cupola. So, this is the cupola and hair cells are present; hair cells are present which end up into this membrane. So, when there is movement of endolymph, now endolymph is endolymph movement happens due to inertia. So, when there is a rotation and there is movement of endolymph within the fluid there. Because, of the inertia the cupola tends to move in the opposite direction that causes stimulation of the hair cells.

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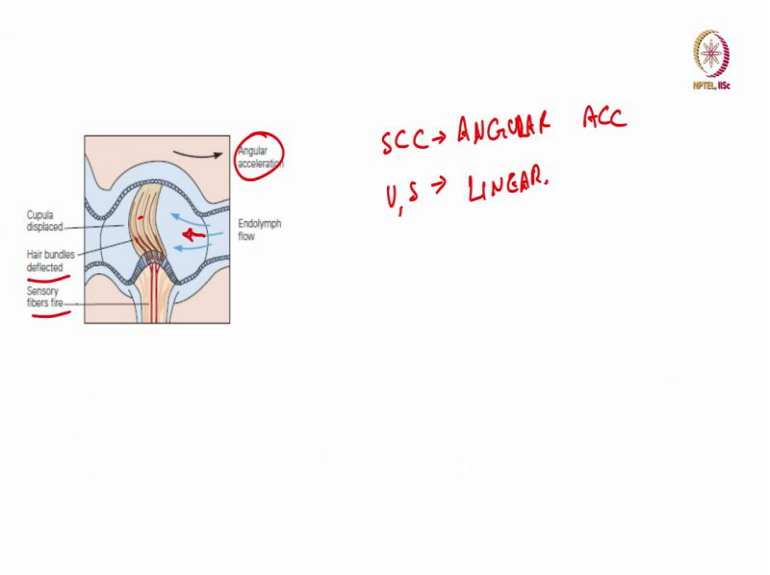

And that produces a signal which is picked up by these nerve fibers and transmitted onto the to the nerve cells which are there in the superior inferior vestibular ganglia. Now, based on the kind of movement you can have angular acceleration, linear acceleration, the different components of that get stimulated. So, semicircular canals are for angular acceleration and utricle and the saccule are for linear acceleration.

So, that is the kind of dynamics which is there. So, mechanism is essentially the same. So, because of inertia there is endolymph flow in the opposite direction and that causes the cupola to be displaced, the hair bundles are deflected and the sensory fibers fire.

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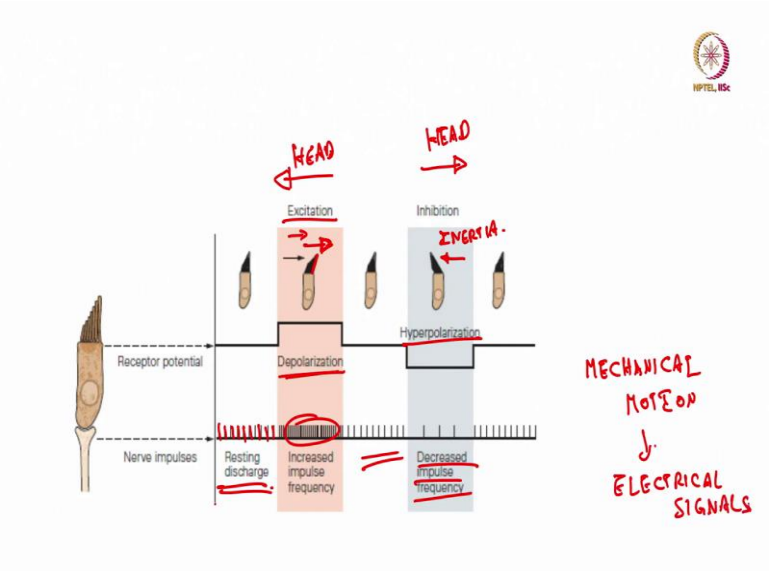

So, that is how this one. Now, looking back into several other kinds of discussion in which I told you that most nervous system mechanisms do not start at 0, they start at a resting level and then step up or step down based upon the requirement. So, similar is the mechanism of the hair cell. So, at rest there is a set of impulses which are generated, and excitation happens when there is depolarization where movement causes the cilia to move in the direction towards the longest cilia.

So, the longest cilia the direction which where there is, when there is movement of the cupola. So, when there is movement of the endolymph in this direction effective moment is in the opposite direction, head movement. So, that causes depolarization and that increases the impulse frequency. Now, when the patient comes person comes back to rest the resting discharge is again restored. Now, the head moves in this direction, there is signal generated in the opposite direction due to inertia.

So, that causes hyper polarization opposite of depolarization and there is decreased signal impulse frequency. So, this is how mechanical motion is converted into electrical signals. So, let us see how this mechanism sort of works.

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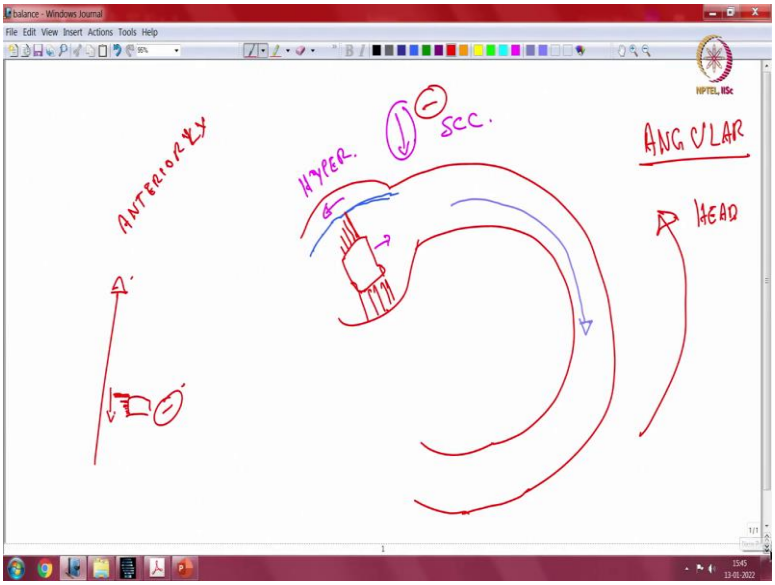

We will start with semicircular canals. So, semicircular canal is I think I will use the lateral semicircular canal, I have a gelatinous membrane over here. It is an exaggerated view, it is it there are multitudes of hair cells within this complex, but for the purpose of understanding that this is.

So, semicircular as I told you is for angular moment, angular moment in the sense that there is rotation which is happening. So, when there is rotation within of the head, the perilymph within this, moves in this direction. So, when the perilymph moves in this direction, the cell in turn moves or the cupola moves towards this direction and then there is that is hyper polarization. So, that causes decreased activity from this semicircular canal. So, decreased activity is a negative stimulation from this side of the semicircular canal.

So, this is how it works. When it is linear motion, the same thing happens in the saccule and the uterical. So, you have linear acceleration and the hair cell which is there moves in the opposite direction and that causes decreased stimulation. So, this is anterior. So, a person is moving in front towards front to anteriorly and that causes this kind of reactions. So, it is not correct to view the systems in isolation. So, we will let see how things happen when they move in uni cell.

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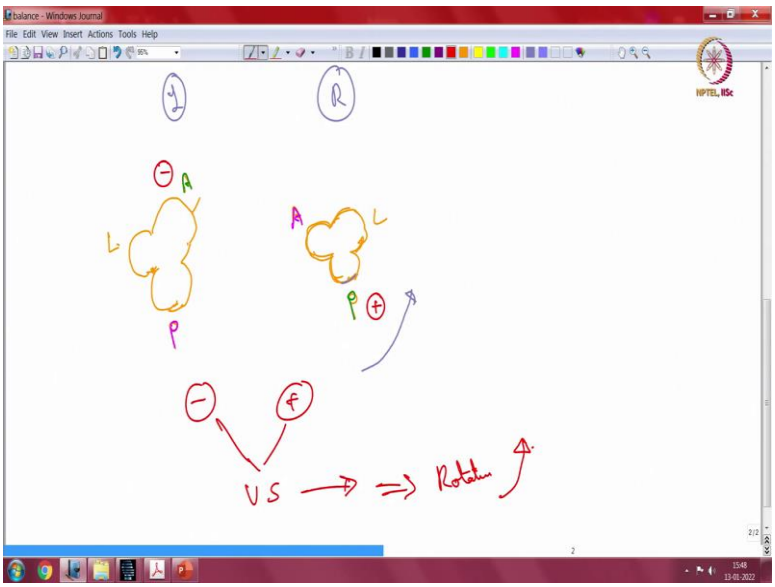

So, I need to draw two or rather three and I am exaggerating these semicircular canals for the purpose of understanding. So, you have anterior, lateral and posterior. So, anterior sorry this is lateral, anterior and posterior right; so, anterior, lateral and posterior. So, that is how it is anterior of one side, anterior of one side is linked with the posterior of the opposite side, then posterior of this side is connected with the anterior of this side.

So, in the sense that so, that is how the linkages, we will see how that linkage happens here. Let us say that the head is having meaning we have we will consider a simple case first and then proceed to a more complex case. So, there is a specific moment in which the posterior semicircular canal is stimulated; so, right side, left side. So, posterior semi-circular canal head is moving towards this side.

So, there is for the posterior semicircular canal here it becomes positive, corresponding opposite side it is a negative. So, that is something which you should recognize because what moment is hyper polarizing on one side turns out to be hyper polarizing on the opposite side. Depolarizing on one side, hyperpolarizing on the other side; conversely if it is hyperpolarizing on this side, it becomes depolarizing on the opposite side. So, that is how it is.

So, you have two kinds of signals, the data the negative signal of here and the positive signal of here is go, goes back to the vestibular system and that is inferred as rotation in this direction so, by the brain. So, that is how the mechanism works. Now, it how does the three-system work? It is based on a coordinate system.

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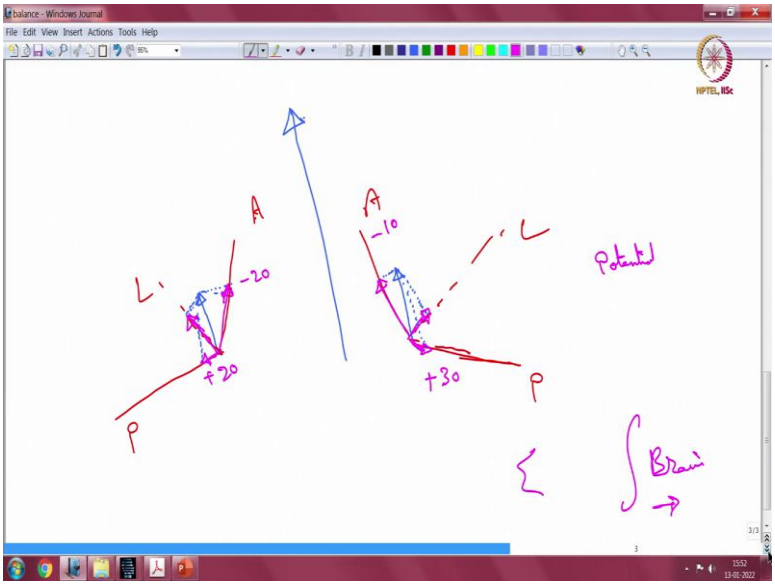

So, let us draw a coordinate system. So, how is this posterior, posterior, lateral, lateral anterior, anterior? Now, if we have the head moving in this direction; so, what happens with that is each of this is represented in three-dimensional space over here, for each of

these semicircular canals. Now, what happens is basically the extent of stimulation is a component in that particular plane.

So, there is a particular component which happens in that particular plane and that is the kind of stimulation which happens. So, you have components of that stimulation happening in all the three planes and each semicircular canal gives a signal for that equivalent intensity right. So now, each of this is in terms of a potential. So, this may be this is towards this side; so, it the direction.

So, the head is moving in that direction. So, basically yeah it would show that there is a rotational component, there is a rotational component which could produces some kind of potential. So, anterior of one side this is negative 20 and then this is negative this will be plus 30 for the posterior, this anterior is right side anterior is minus 10 and this is plus 20. So, something like that. So, I just gave it as numbers to illustrate the point. So, there are components.

So, you do not have pure systems which look at you know one particular entity. So, rotation in general is through semicircular canals, the utricle and cycle take care of the vertical and horizontal movements. So, each of these produces some amount of signal in the relevant systems and these systems are all summated and computed within the brain and that gives you a that gives a sense of that gives a sense of position to the head as such. Now, the vestibular system is important because, it forms very fast systems to two or two parts of the different parts of the brain.

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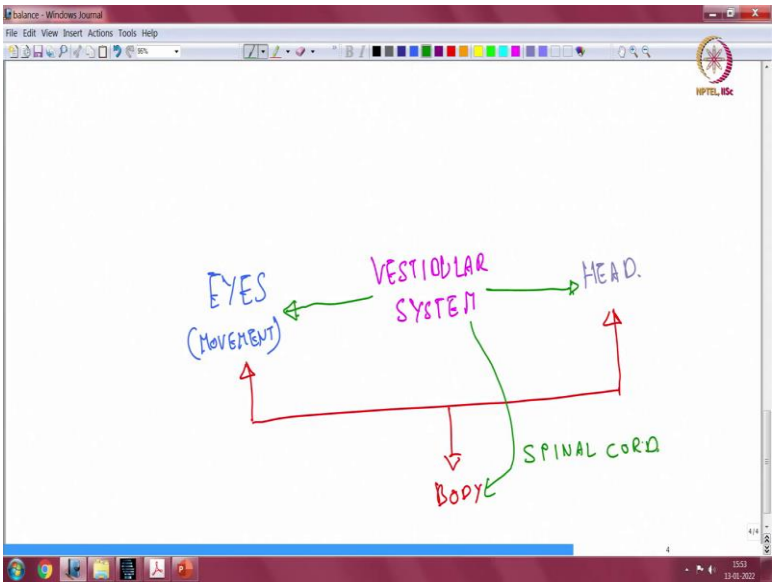

So, the vestibular system integrates two, three different functions. So, one is the eye, eye as a movement and the other component is the head. So, it needs the human body, or any organism incidentally needs to connect eye movement with head movement and this in turn has to be core coordinated with body movements. So, the vestibular system integrates this thing.

So, it provides signal to the eyes, it provides signal to the head and through the spinal cord it provides a signal to the body. So, that is how the vestibulospinal tract is there when I spoke about the spinal cord, I did highlight about the spinal vestibular system and the vestibular spinal fibers which go down through the spinal cord. So, the vestibular system sort of integrates data and outputs data to each of these things.

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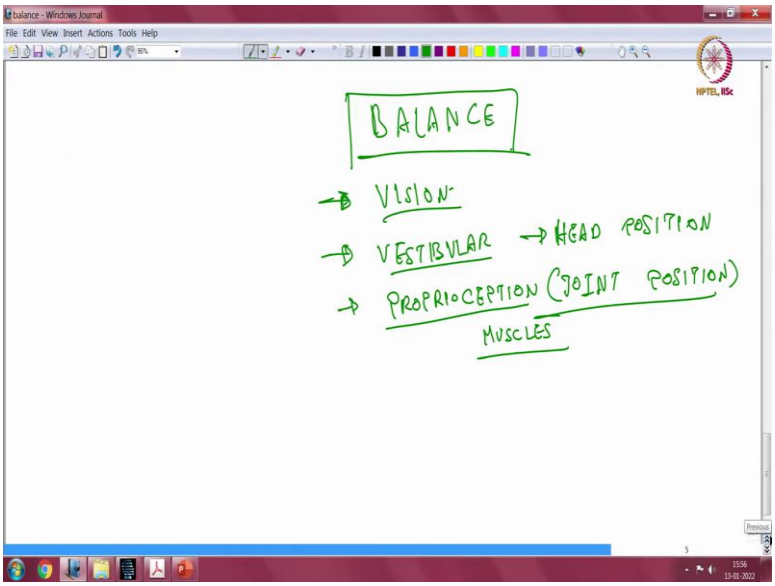

So, when we speak about balance. So, balance is in general for the whole organism. So, there are three components as I spoke about: one is the primary one is vision. So, when you are walking, when you are sitting, when you are standing; there is enough visual input to say how your head is in relation to the horizontal or to whatever meaning you get visual idea of how things are in relation to yourself.

The second place second thing is the vestibular system which says which not only says how the body as such is in it gives specific information regarding to head position, then the third system is proprioception. So, this is joint position and joint position is acquired from different receptors at joints and from muscles by the state of activation, all of this is sensations which is taken up for proprioception.

So, balance of the individual organism is dependent upon these three things, you cut out two of them the person is in significant has significant problems. So, one of it is compensated as the either a vision problem or there is a unilateral vestibular problem or there is some problem in proprioception or sensation, it gets compensated. The system is very redundant and takes care of itself. Incidentally balance is a very fundamental issue.

I think I spoke about this earlier also in the same context, that balance is something which an organism very preciously guards. So, it is maintained through very redundant systems, vision is completely different from vestibular which is completely different from so proprioception. So, in summary this is how the yeah; so, I did not; I did not

speak about the effector mechanism. So, effector mechanisms are for example, like this so.

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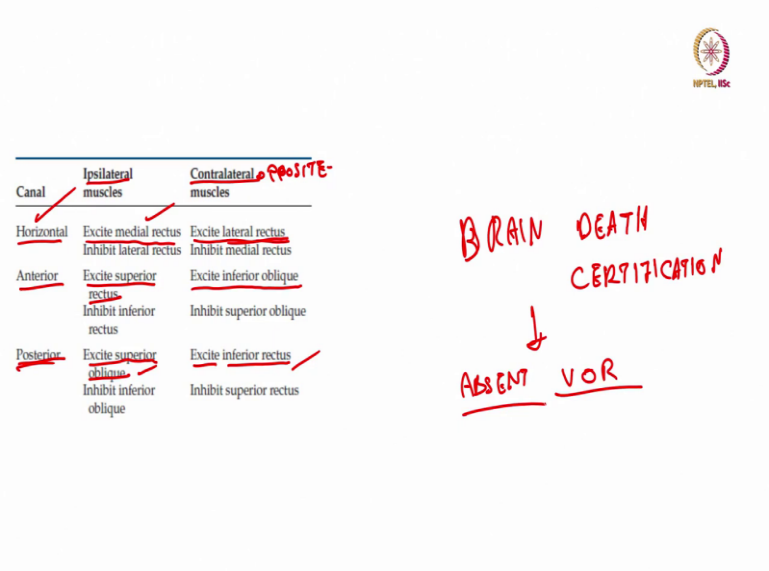

So, each what is that horizontal canal is directly connected to the medial rectus of the same side and lateral vectors of the opposite side, opposite. The anterior is connected to the superior rectus and inferior oblique of the opposite side, superior rectus same side, inferior rectus opposite side, posterior canal for superior oblique and inferior vectors of opposite side. So, they are all directly connected.

So, when there is; when there is stimulation from horizontal you know that it is going to excite the same side medial rectus. It will you would have movement towards the medial rectus is towards the nose, excite the lateral rectus of the opposite side that opposite side I goes away from the nose. So, that is lateral rectus, that is how you can remember. Anterior is the superior rectus above, superior rectus eye going up, inferior oblique is inferior oblique also shifts the eyeball up, but in a more different direction.

So, similarly for the posterior which does the opposite of the; opposite of the anterior. So, there are direct connections between the vestibular system eye muscles. So, that you know there is a seamless that is why vestibular ocular reflex which I have discussed in the in mission is important because, that is one of the methods by which you have default moments programmed in. So, there are so many of these default moments, they are basically reflex mechanisms.

So, reflex mechanisms again if you remember from the spine class and the basics of motor system, they are ground level servo control systems and they function autonomously. So, these function autonomously and to give you the extent of importance if you if anybody has read about brain death certification, you would see that you know you absent vestibular ocular reflex is one of the criteria.

So, that is a fundamental reflex. So, that indicates the functionally one of the indicators of the functional indicate integrity of the brainstem. So, when the brainstem is only when the brainstem is functional can this pathway between the ear and the eye be intact and you can actually you do something called as a cold calorie test by which you can determine the integrity of the system.

So, you put cold saline or hot saline in the ear cavity that stimulates the middle ear by reducing changing in changing the temperature and that produces some movements within the semicircular canals. And, in case of an intact brainstem that movement in the semicircular canals get reflected in the eye movements. So, that is the principle of the vestibule of the vestibule ocular reflex and its utilization in brain stem dysfunction significant brain stem dysfunction.

So, the vestibular pathway is important, the system is beautiful you know you it does principal component analysis of any given vector. And, then transmits the data from two independent sensor systems, the sensor systems are integrated much higher within the brain stem and within the brainstem yeah. So, I have not spoken about the pathways subsequently.

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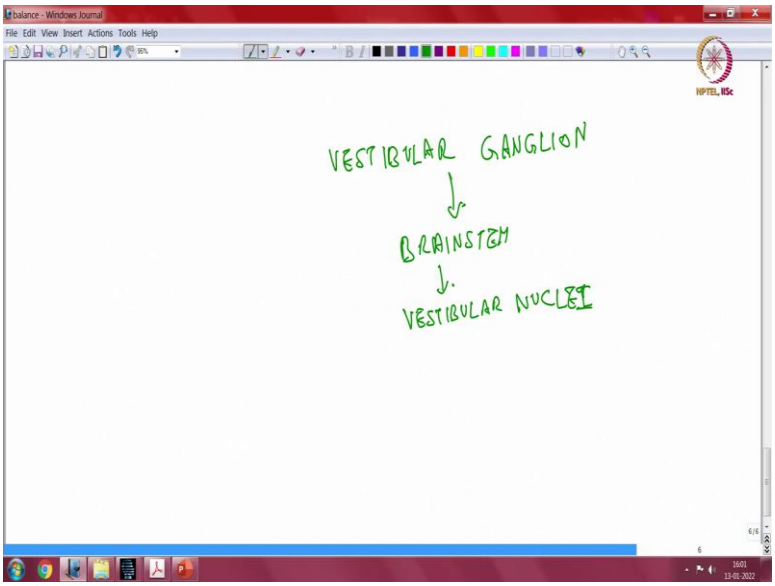

So, from the vestibular nucleus vestibular ganglion, it goes into the brainstem where it goes into multiple sets of vestibular nuclei. They have specific coding, in the sense that each of these canals go into specific nuclei and each of these nuclei internal are connected to specific eye muscles through interconnecting fibers through the to the neck to ensure neck posture to the body.

And so, there is a lot of regulatory mechanisms built into it. So, that is how the system works. So, it is a very elegant mechanism to ensure that the dynamic position of the head and body is maintained.

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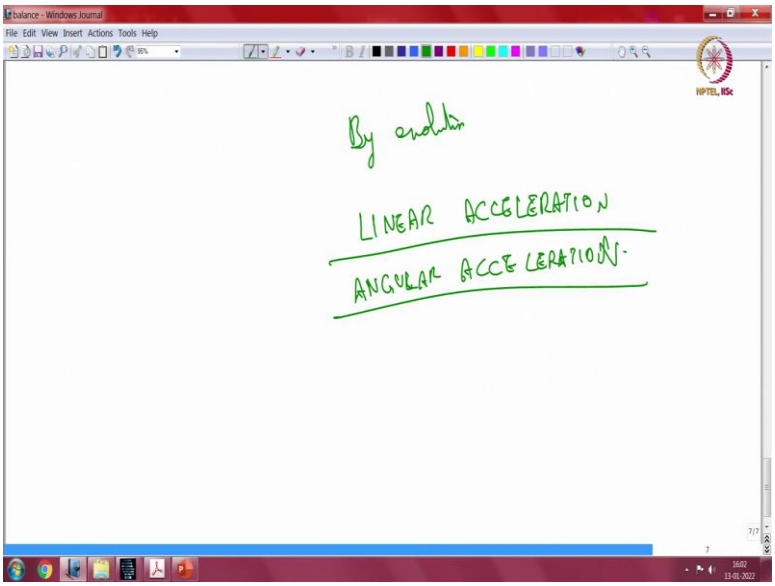

And it is of interest to note that the system already in a meaning by evolution understands the concept of linear acceleration and angular acceleration. So, it is a biological you know biological sensor system. So, there are there is a different sensor system for linear acceleration, there is a different sensor system for angular acceleration.

It is split on both sides of the head to ensure that there is fidelity of data, maybe there is something else in regard to you know calibration of the body movements and things like that. And that is maybe the reason why I have two sets of them on both sides of the head. And surprisingly it is connected with hearing; mechanisms incidentally are very closely related with that kinetocelia and celia which hyperpolarizes.

The mechanism is exactly similar to the hearing mechanism in which potassium plays the major role in depolarizing and hypopolarizing these cells. The concept of a resting membrane activity is there which is modulated by movement. So, dysfunction within the vestibular system is known due to several diseases, some of which many of which are self-limiting.

And interestingly say damage to the vestibular system is you know it gets sorted out in a period of time. Even if there is complete damage to one side vestibular system as happens in some diseases like for example, we treat vestibular schwannoma which is a tumor in that location; patients do have a problem with balance, but it is not persistent.

So, when you operate out the tumor, it is not that their vestibular system is restored, but the damage does not seem to affect the affect people significantly. So, that is the beauty of the redundancy or hyper redundancy which is built into balance and posture. So, it is a beautiful system, relevant but has its you know it is something which can be replaced by several other mechanisms such as vision, position, sense and maybe even one side.

So, one side functioning is sufficient enough to maintain body posture and normal activity. So, I think with that I cover some of the issues related to the vestibular system and how the vestibular system is important for maintenance of balance, linear acceleration and how it deals with linear acceleration and angular movement in three different planes.

Thank you.