Microsensors, Implantable Devices and Rodent Surgeries for Biomedical Applications
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Hello everyone, welcome back to the module on Rodent Neurosurgery. After having gone through the brain anatomy and brain surgeries of craniotomy and the stereotactic techniques, the next valuable addition to the whole course is about spinal procedures. As you all know, the central nervous system comprises the brain and spinal cord. So, for those dealing with neural engineering, neural experiments, or neural behavioural science, the spine and spinal cord are integral parts of the whole neural science. Keeping that in mind, we have included spinal neuroanatomy, spinal operative approaches, the requirements and setup needed, and the possible experiments in this particular field, which will be covered in the following sessions. Today's session will mainly focus on spinal neuroanatomy.

It is very different from what we have been dealing with in the last few sessions. The vertebral anatomy, the anatomy of the spinal cord, and the vascularity are all very important to understanding the various applications of this knowledge in spinal-related experiments. With that brief introduction, let's look at the overall session that I am going to cover: the central nervous system, spinal skeletal system, spinal cord-vertebrae relation, which is very important to understand, then the spinal dissection, discussing what layers are needed to expose the vertebrae and the spinal cord, and briefly about spinal vascularity and the spinal cord structure and circuit. That is the entire outline. In the first half, I will cover the top three, and in the next half, I will cover the remaining topics.

To begin with, you all should know what exactly the rat nervous system is composed of. This is a sort of holistic picture where, in one image, you can see the entire length of the central nervous system. The idea is that it is very important to understand the relationship of the spinal cord with the brain and, of course, the nerves that come out of it, and the overall gross anatomy of the entire central nervous system. Since we are dealing with different sections and sessions, you should get a bigger picture of where the spinal cord is, how it relates to the brain, and how it conveys information to various parts of the body. This is very important to understand. As you all can see here, this is the rodent brain that we have dealt with throughout. You can see that there is the olfactory bulb, the entire cerebral hemisphere, the cerebellum, and underneath it, the brain stem.

When we talk about the spinal cord as such, that is where it starts from. This is known as the cervical medullary junction. If you all remember the previous sessions on neuroanatomy, we discussed something known as the brain stem. The brain stem has three parts: the midbrain, pons, and medulla oblongata. It is this medulla, which is the terminal part of the brain, that continues downwards as the spinal cord.

This junction is very critical. After this, the vertebral anatomy starts with the cervical vertebrae and thoracic vertebrae, covering the entire length of the spinal cord. You should remember that various cable-like structures come out from the spinal cord. That is how the nerves are arranged, and the spinal cord is like a big cable. Many of you might be electrical or electronics engineers and can draw a good comparison.

We are dealing with an electrical system, but this is a large, live organic neural system that sends impulses, which are then conveyed like any other electrical cable or wires throughout our body to transmit information from the brain to the periphery, be it a muscle, gland, or any other organ in the body. When we deal with the different structures of the spinal cord, it is essential to note that it is like a tube starting from the brain with a central canal filled with fluid. Similar to the layers covering the brain, such as the dura mater, arachnoid, and pia mater, the entire covering continues along the length of the spinal cord. The cross-sectional anatomy of the spinal cord will be discussed in a few slides. However, you should remember that this entire brain covering continues downwards, and if the vertebral canal is outside, there is a dura, an arachnoid, and a pia. Only then does the spinal cord structure become visible.

To get a clear view of the spinal cord, one has to dissect it through multiple layers, and it is very important to understand how to approach and expose the spinal cord, which is a thin, slender, soft tube within a huge skeletal system, with multiple layers covering it. This is the orientation that you should remember throughout the entire course because unless you remember it, it is difficult to understand the relation with the skeletal system, the relation with the brain, and its various functions. With that introduction to the entire nervous system, let’s look at the paraspinal musculature. This is very important to understand because it is not necessary to remember every single muscle, but you should understand what kind of dissection is required and what structures need to be cut to expose the underlying vertebrae. As soon as the skin is peeled and folded upwards, revealing the entire musculature, right from the cervical medullary junction to the tail, you can see that the rat's skin has been completely peeled off and folded upwards, like that, to reveal the musculature.

That is the spinous process in the middle, and in a bit, you will understand what these spinal structures are that I am describing. Try to focus on these muscles around the spinous process and their function, which is to turn the neck, lift the upper limb, or move the hip joints. The orientation has been shown here, with the back being the area shown. The back of the rodent is called the dorsum, and the belly is called the ventral side. This is the dorsal aspect, and it continues as a tail, as shown here. Once you are oriented, try to focus on the girdle muscles: the forepaw girdle muscles and the hindpaw girdle muscles, which are important for stabilizing the hindpaw and the forepaw.

So, when we deal with the peripheral nerves and the muscles they innervate, we can discuss more about these muscles, to understand the vertebrae exposure and maintain that exposure before you do a laminectomy. Laminectomy is a procedure where you remove the posterior back, the covering of the back portion of the vertebra. We will deal with vertebral anatomy again later. These muscles have to be cut open and maintained laterally, all right? You will be making incisions here and then exposing these muscles only to enter the vertebral canal, which is the spinal canal.

So, that is very important. It is also important to know which part of the vertebrae you are going to deal with. For those experiments that require only the upper limb motor responses or anything to do with the forepaw, I will be using "upper and lower limb" because of the switch from human to rodent. Forepaw is the word that we commonly use for small animals.

So, if it is only the forepaw, then it is mostly cervical thoracic vertebrae, and if it is the hindpaw, it is lumbar vertebrae and the paraspinal muscle is the thoracic vertebra. So, cervical or the cervical region refers to the neck; this is thoracic, which is the chest and abdomen, on the dorsum it is called the thoracic vertebra, then the lumbosacral and coccygeal, which refer to the tail. So, the lumbar region refers to the hip sacrum and the hip sacrum, the tailbone before it becomes the tail, and then the coccygeal bones, which are connected with the tail. These are the various segments of vertebrae that are covered densely with this paraspinal musculature, all right? So, let us look at the entire spinal skeletal system that I just described.

The idea of this picture is to get an orientation as to how the entire spinal skeletal system is assembled with the cranium, which we discussed in the last few sessions. So, up until here, we have completed the discussion. So, if you all remember, that will be the upper jaw, and that will be the frontal bone somewhere there—the bregma, parietal bone, interparietal bone, and the occiput (occipital bone) covering the cerebellum. From here starts the atlas, which is C1, the first cervical vertebra. If you all remember the terminology "atlas" from Greek mythology, which is holding a globe, that is the cranium, and that is how the terminology has evolved "atlas," which is holding this globe. So, from then onwards, it is all cervical vertebrae, as I said, and there will be some other thoracic vertebrae, lumbar, sacrum, and coccygeal vertebrae.

This is how the curvature of the spine is also maintained, which is very important to understand. This is called cervical lordosis, this is thoracic, this is kyphosis, and this is normal lumbar lordosis. These curvatures are very important in humans, and in rodents, it is enough to understand what sort of postural adjustment is required to approach this particular vertebra and how to make sure that this curve becomes that way so that your approach to each of the cervical vertebrae becomes a bit easier. That is important, and of course, you will be able to know the relation of various spinal cord segments.

This is the spinal cord, and this is the cross-sectional MRI if the section goes in the middle, and that is the midsagittal plane. This is how it would look. So, you can see the sagittal section of the brain and then the cervical cord. If you all remember, I said there are multiple layers before we approach. So, you can appreciate this skin, subcutaneous tissue, then the muscles, and then the spinal cord before the vertebral column. So, skin, subcutaneous tissue, paraspinal muscles, which we just discussed, then comes to the vertebrae—that is the spinal vertebra—that is this. After that layer, there are multiple meningeal layers of dura, arachnoid, pia, and only then will you be able to visualize the spinal cord.

So, there are almost five layers above the cord, and the toughest layer is going to be the vertebral layer, which has to be dealt with using hard instruments and bone rongeurs, making sure the underlying jelly-like tube is not damaged. Similar to what we had with brain surgeries, where you do a craniotomy to remove the hard bone before you approach the soft brain tissue. Similarly, that is exactly the reason why you need to understand the various anatomical details before you approach the spinal cord so that the entire surgical outcome is good and the experiment goes as expected. So, one has to look at the entire skeletal system of the rodent; this is where the vertebral column is arranged on the dorsum.

As I said earlier, this is dorsum, and this is ventral, all right? So, this is the rostrum, which is towards the mouth of the organism, and that is caudal. I am trying to use these terminologies as often as possible so that you will also get familiarized because most of these anatomical terms are very important when we deal with surgical techniques and various surgical strategies. So, if you remove all the other skeletal systems, what is left is this spinal skeletal system, where you can appreciate the various segments of vertebral anatomy that I just described. As I said, that is where the skull stops.

So, this will be the occipital bone, interparietal bone, parietal, and frontal, all right, and then the other facial bones here. That is the cut-off for the cervical medullary junction where the brainstem becomes the spinal cord, and the spinal cord goes the entire length until it becomes the coccygeal segment. So, that is the atlas, which is the first cervical vertebra, then the axis. The axis has the odontoid process, along which the head can rotate on the central axis, all right? Then comes the remaining cervical vertebra until there is the thoracic vertebra, lumbar vertebra, and sacrum, and then it becomes the coccygeal vertebra. From there, and then it evolves into the tail bones, which are known as metatarsals, all right?

This is how the entire spinal skeletal system is arranged, and as I said, when you want to approach the central core, which has the spinal cord, you will be removing the muscle layer there, and then the subcranial tissue, then the skin, all right? Next, it is the spinous process this is to have a good orientation, and I am trying to explain that you will be approaching from the top. The first incision will be on the skin, and then once you retract those skin folds, then the subcranial tissue, muscle, and bone, all right? We will be using these terminologies as often as possible, so every single slide is a sort of revision for you to remember and orient yourself to approach the spinal cord. This again clearly shows all the vertebral classifications into different regions altogether.

So, there are a total of 58 vertebrae, all right? So, how does it form 58? This you can understand here. There are around 5 cervical vertebrae, including the atlas and the axis, then 13 thoracic vertebrae, 6 lumbar vertebrae, 4 sacral vertebrae, and then there is one caudal vertebra, and the 30 tail bones, all right? So, that is how there are 58 vertebrae that form. It may not be necessary to understand every single vertebral section, but it all depends on what sort of study you are dealing with.

If your study is mostly about this skeletal system which is not the neural experiment, but if it is like a focused cervical vertebra approach and then you are trying to look at dorsal root ganglion or the cervical spinal cord then you need to understand how the cervical vertebrae are going to be used. And how the cervical vertebrae is oriented which vertebrae you are going to approach and how do you expose the posterior element of the cervical vertebrae so that you can approach the spinal cord in the end. So, it is very very important to understand what spinal cord segments are. For example, if this is the spinal cord it is not uniformly you know smooth inside the vertebral canal. You will see a lot of the spinal roots that exit each of these spinal cord sections.

Similar to what you see in the vertebral system even in the spinal cord there is an arbitrary division called the cervical cord, thoracic cord, and lumbosacral cord and then it tapers down to become the coccygeal part of the cord segment. So, there are this spinal cord segment similar to the vertebra. So, you need to understand which cervical vertebra cord segment comes under which cervical vertebra. So, just because there are some 58 vertebrae there are no 58 spinal cord segments.

Cord ends somewhere there you know. So, that is how the spinal cord goes in and as you can see in these next few images you will be able to appreciate where the cord ends. So, for the 58 vertebrae to accommodate the spinal cord which is shorter obviously, multiple segments are coming in and covered by a single vertebra. For example, this circle vertebra covers around 4 to 5 cord segments all right. Even in a cord segment, there are C1, C2, C3 up to C8 all right. Similar to what we see in the cervical vertebra where is C1 vertebra C2.

The C1 vertebra is known as the atlas, C2 vertebra is known as the axis. So, similarly, you have C7 vertebra. So, there are 7 cervical vertebrae, but there are 8 cervical spinal cord segments all right. So, similarly, there are 13 thoracic vertebra segments and then there are L5 lumbar segments and 5 sacral segments. So, you will understand it further when I deal with the vertebral column and spinal cord relation.

So, this is the orientation of how the segments are arranged within the different spinal vertebrae. So, it is also better to know briefly what it would look like. This is the single vertebra as you can see we have taken one single vertebra like that and that is what we are trying to look at in detail. A single vertebra how is it oriented, what are the different parts of the vertebra and which vertebral part you will be removing to expose the spinal cord that is the whole idea of this. So, as again this is dorsal, this is ventral, this is dorsal, this is ventral.

This is the side view, this is the APU when you see it in front after you take a cross-section you see from this is dorsal, this will be on top. So, if you can feel the spinous process on the back of the rat or when you palpate it, when you feel it you will be feeling this spinous process on top of the animal's back of the animal. This is the belly and the belly. So, that is ventral, this is dorsal alright.

So, that is the side view. This is how the spinal canal spinal vertebra will be arranged. So, what the structure that comes right on top which is palpable is the spine of the vertebra neural spine. So, that forms the lamina. So, if I were to put spinal cord here this is how it would look like.

So, this again I will be dealing with. So, the reason why I am trying to orient you with the spinal cord and vertebra is to approach the spinal cord so that bone structure should be removed which is called laminectomy. Actomy as I said earlier is removal, removal of the lamina is laminectomy alright. So, you will be removing the spinous process with the bone rongeur. So, either you drill or use the bone rongeur straight and remove this part of thing then you will be able to see the outermost covering of the spinal cord. And there are other parts of the vertebra where one vertebra fuses with the other right.

So, this will be one vertebra and this will be another vertebra behind it. And then like that it continuously forms a spinal skeletal system in this manner. Each vertebra is joined along with the other at these joints which are these joints it is called zygapophysis joints and anapophyses joints. This is the centrum the body of the cervical vertebra which again is fused with the vertebra behind with what is known as intervertebral disc space alright. So, when there is a disc prolapse there is a nerve that comes out that will be compressed.

So, the spinal anatomy is again 3 dimensional just like the brain anatomy and it is very important which part you know to it is very important to understand the relation of one structure with all the other structures to get a full 3 dimensional orientation. Hence multiple pictures and images try to orient you this is how it is going to be within the body of the rodent. So, this picture beautifully explains the relation of various other structures that I was just explaining. So, this is how the spinal cord is arranged. So, that is the thin slender spinal cord is arranged within the hollow spinal canal alright.

So, this is this and this is that this is the side orientation this when you take a section in the middle and you turn it around this is how it would look like. The spinal cord is right in the centre and as you can see try and appreciate all the coverings that are seen here now. So, this is the innermost part of the spinal canal or the vertebra after which this layer is the dura mater. So, if you remember from the brain anatomy this is similar covering which is tough is the dura mater, then the thin arachnoid which covers the entire neural structure, then the pia mater which is right on the spinal cord and follows in the various grooves and folds. So, these three coverings have to be open generally these two will be handled pia will be stuck to the substance of the spinal cord itself.

So, once we cut open these structures, only then will the spinal cord be completely visualized. Before that, multiple vessels surround the spinal cord, which we will discuss when we cover vascular anatomy. However, it is also important to understand how the nerve emerges and how this peripheral nerve arises. The brain and the spinal cord make up the central nervous system. There is also something known as the PNS, which is the peripheral nervous system. The CNS is the central system, while the PNS conveys messages from the CNS to the periphery, such as muscles, glands, or any other organs that receive nerve supply.

So, where does the PNS start? It starts right from this foramen. This is the dorsal rootlet, and that is the ventral rootlet. The dorsum refers to the top of the body, and the belly portion of the body is ventral. The dorsal rootlet is the root, essentially the origin of the nerve, which eventually forms the peripheral nerve after going through various branches as the plexus. The dorsal rootlet carries sensation, and the ventral rootlet transmits motor information. This is the afferent, and that is the efferent. I think this is a basic neural science that most of you must be familiar with, but this is how it is arranged within the spinal canal.

From the dorsal horn of this grey matter, which is in the shape of an 'H', the dorsal rootlet arises, and from the ventral horn of the spinal cord, the ventral rootlet arises. Both of them fuse to form this peripheral nerve, which also contains what is known as the dorsal root ganglion. This structure is called the dorsal root ganglion, which is very important and is the focus of many research studies related to pain or sensory phenomena. This is one structure that is often targeted, and it is housed in the vertebral foramen, between the vertebrae when it emerges. The dorsal root ganglion is associated with sensation and carries impulses toward the brain. Once it emerges, it divides into the dorsal rami and ventral rami.

The ventral rami fuse with multiple other nerves to form what is known as the plexus, which then divides into various branches to form the final peripheral nerve. This entire system is the peripheral nervous system. I was trying to introduce another concept at the interface between the CNS and PNS, where this transition occurs. Today's discussion will focus solely on the spinal cord itself, so that is the anatomical orientation of the spinal cord and the peripheral nerves.

This is to help you with the three-dimensional visualization of the various structures we just discussed. Those are the paraspinal muscles we discussed, and that is how they are oriented, along with the cranium, frontal, parietal, and occipital bones. Try to visualize and understand the three-dimensional relationship of all these structures. That is the entire skeletal system, and today's discussion is, of course, about the spinal skeletal system. The idea was to orient you as to how the spinal muscles are arranged in and around the skeletal system and how the spinal vertebra continues from the cranial vertebra.

Here you can see the axis (C2), and above that is the atlas, followed by the other vertebrae. You can see the intercostal nerves and the housing of various viscera ventral to the spinal canal. If you want to approach the anterior or ventral surface of the vertebra, you would use a thoracotomy at this level and a laparotomy at this level. We approach the spinal cord only through the spinous process from a top-down approach. That is the entire skeletal system in a three-dimensional orientation.

You can see the intervertebral foramen through which the nerves emerge to supply the limbs and other organs. That is the large spinous process I mentioned, and these are the transverse processes that emerge from the spinal vertebral body. The next important aspect is the relationship between the spinal cord and the vertebrae. It is very important to understand. As I said, remembering the exact number of vertebrae and spinal cord segments and where exactly the spinal cord ends and the vertebral column begins can be difficult. However, it is crucial to have at least a rough idea. These days, we have imaging techniques to help us understand this, but in surgery, we still need to rely on various surface and skeletal landmarks before approaching particular spinal cord segments.

So, this gives the exact relation where you can see the first cervical cord segment. Cord segments are divided as per their branches which come out the dorsal and ventral rootlets. Imagine if this is the cord and that is how it would look like. Based on the branch exit of those branches it becomes C2, C3, C5, C6, 7, 8 so on and so forth. But then the relation with the vertebral body if you see C 1 is actually at the rostral part of the C2 and up to C6 it roughly corresponds with the vertebra.

But later on, you see that there is a big jump the T4 body has T6 and T5. And if you go on if you look at this the middle of the L2 body there is a jump to S3 and if you look at T11 there is already L1 coming in. And if you look at the L1 body there is almost the addition of 5 cord segments here. So, that is how the entire spinal cord is housed in the extensive spinal vertebral system. So, how do we remember? One way is to do the preoperative MRI you know this is the preclinical MRI which is not available in most of the centres at least not really common in India.

So, but then this will this available from the literature you can see what I meant. You see that is the this is the mid-sagittal section. So, sagittal MRI is where the section goes through the midplane as the rat is lying in its anatomical position where this is the dorsum is the ventral rostrum and the caudal is the tail portion is the mouth portion there. So, with that orientation, you can see these black structures are the spinous process of the spinal canal all right. As I said earlier within the hollow spinal canal this is there is a very thin line here lies the spinal cord this is the outline of the spinal cord and you can see this body.

Now this is the C2 body and that is C1 is the atlas body. So, try and visualize if there was a bone here that is how it would look like all right within the central core there is a spinal cord passing through. You can see here that this is the intervertebral disc between two bones there is a disc joint which is form so, known as the intervertebral disc and look at the relation between the vertebra and the spinal cord segment this C1 segment is almost towards the end of the C1 you know C5 C6 C7. So, C7 is under C6. So, it has already started moving whereas, if you look at this the disparity is very clear there is a beautiful image where multiple MRIs have been fused something known as a scout image and then you can see that the entire vertebral column is arranged in the order and then you can see the corresponding spinal cord segments. So, to remember this relation easily this is how we use the relational cord and vertebra in humans.

So, I sort of took that rule and see whether it fits into the rodent vertebra as well. So, fortunately, it does and you can see until C 6 the cord segment is the same right? So, then up to T6 after C6 you need to add at least 1 to know the cord segment till T6 you know the C6 is the same. The cord segment to T10 you need to add plus 2 that is if it is T10 the cord segment that will be within the T10 thoracic vertebra is the T12 cord segment. If it is T 8 vertebra you will be dealing with T you can understand by you know I have look at this you will understand it better.

So, T9 is T7. So, you are adding plus 2 you know and then you see T6 it has a T8 segment that is again plus 2. So, that is the importance from 4 from C6 to T5 or you will be adding at least 1 cord segment. So, that is plus 1. So, T13 will have L3 to L5, L1 will have L6 to S1, L2 will have S2 to S4 and the spinal cord ends at CO3 which is coccygeal 3 all right. So, L4 vertebra the spinal cord of the rodent ends whereas, in humans, it ends at the L1 level L1 2 junction.

This is where it would end in humans, but in rodents, the spinal cord extends to the L4 vertebra. So, if you are exposing the sacrum and coccygeal and all that you will you will not be able to visualize the spinal cord and that is very important to understand if you are trying to approach the coccygeal segment of the spinal cord which controls its bladder and other autonomic functions. So, if you want to expose the L4 spinal cord it is it will be wrong to expose the L4 vertebra all right because it will be housing the coccygeal spinal cord segment and not the L4 vertebral segment is the importance of this particular slide and it is very important to understand which is the spinal process that you will be exposing and what is the spinal cord segment that will be in relation with that particular vertebra. Anyway, the previous table will guide you directly and if at all you want to remember this is one way to remember up to T6 how much you need to add and up to T10 and up to T12 so on and so forth.

So, that sort of covers the entire skeletal anatomy so, that ends today's session. So, to summarize I have covered the entire skeletal anatomy of the spine as such and it is important to understand further how the spinal cord is related what is the structure of the spinal cord and what sort of applied anatomy it can be used for the spinal surgery as such. So, after the vertebral anatomy in today's session, we will deal with the spinal cord segment in the next session. Thank you all.