Introductory Neuroscience and Neuro-Instrumentation
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Lecture 27
The inverse problem and EEG source localization

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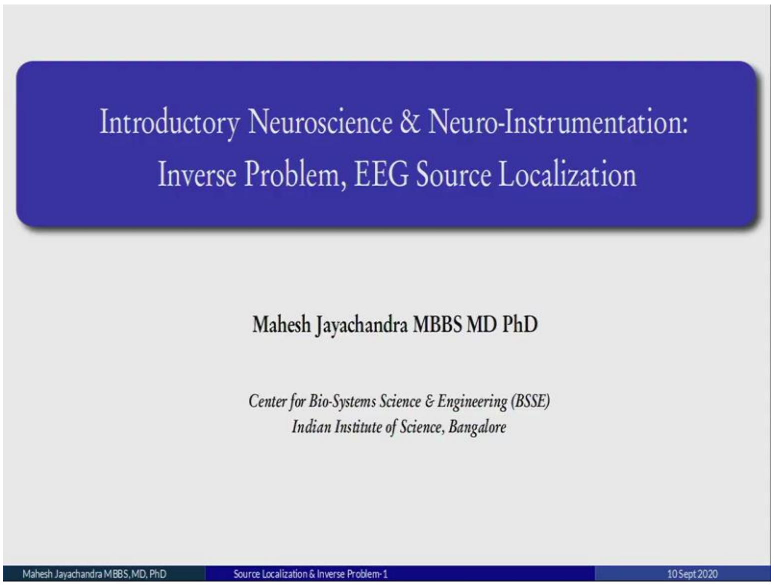

Introductory Neuroscience & Neuro-Instrumentation: Inverse Problem, EEG Source Localization

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Introductory Neuroscience and Nero-Instrumentation: The inverse problem and EEG source localization. This is a slightly complex and theoretical lecture, so please bear with me.

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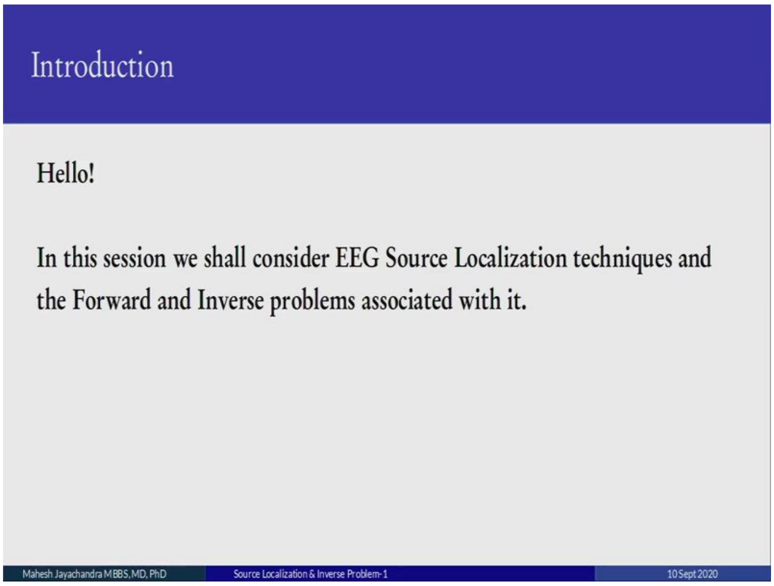

Introduction

Hello!

In this session we shall consider EEG Source Localization techniques and the Forward and Inverse problems associated with it.

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So here we will consider EEG source localization techniques and the forward and inverse problems associated with it. What it means is that we are recording from the scalp. Now, which part of the brain, which brain areas contribute to EEG? Now can we do that just from the scalp electrodes? Can we figure out which areas cause different EEG and ERP components? That is what this lecture is about.

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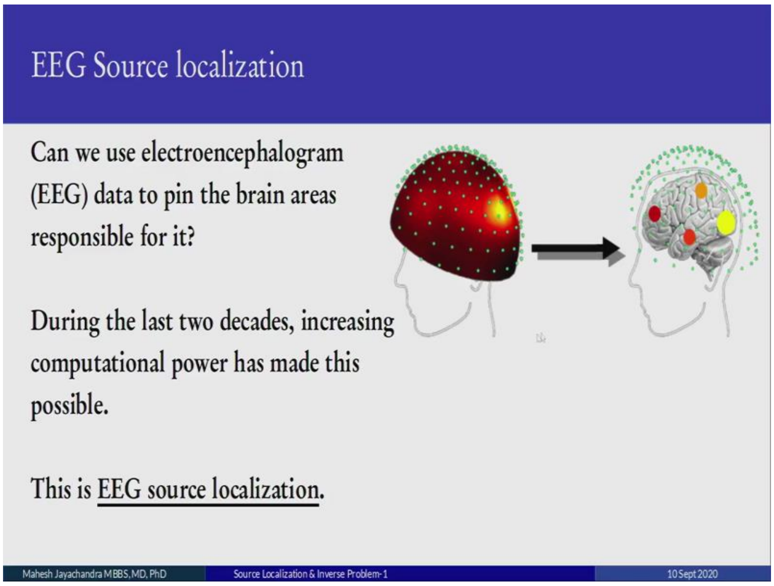

EEG Source localization

Can we use electroencephalogram (EEG) data to pin the brain areas responsible for it?

During the last two decades, increasing computational power has made this possible.

This is EEG source localization.

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So during the last two decades, our computers have become more and more powerful. The computer's computational techniques used by earlier neurophysiologists were hamstrung because they were very weak compared to what we have with us now. The computational power of an android smartphone is many orders of magnitude more than what the early neuroscientist.

When I say early neuroscientist, I am talking about the people from the 50s and 60s which are already using computers what they had. So the thing is we are recording from the top, all these green dots are electrode positions and using these can we work backward and see which brain areas contribute or cause this electrical activity on the brain? So this is EEG source localization.

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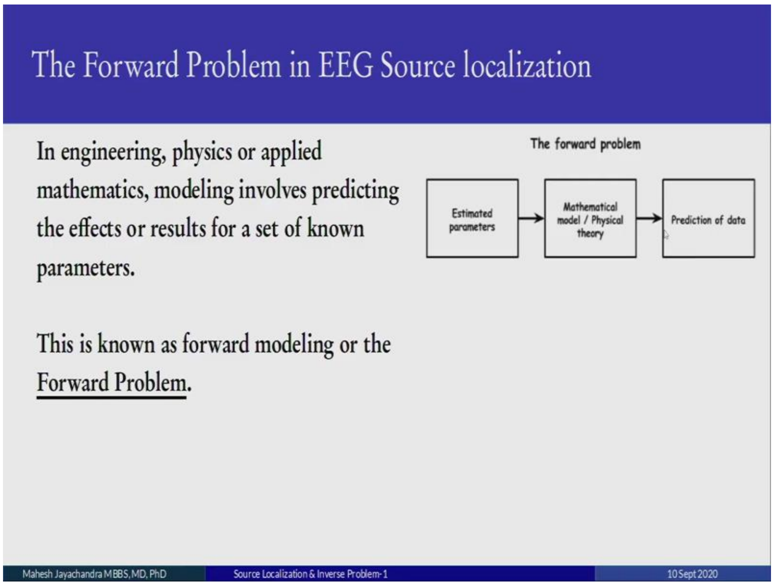

The Forward Problem in EEG Source localization

In engineering, physics or applied mathematics, modeling involves predicting the effects or results for a set of known parameters.

This is known as forward modeling or the Forward Problem.

The forward problem

Estimated parameters → Mathematical model / Physical theory → Prediction of data

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So the forward problem. So in engineering physics or applied math, modeling involves a set, involves predicting the effects or results of, for a set of known parameters. We know what is happening. We develop equations and we have a mathematical theory and then we can predict how that data looks like, like so on the right you have estimated parameters that gives rise to your mathematical model or physical theory and then you have a prediction of data. So this is the forward problem. As long as you know all this and this is reasonably good, your theory, you would have a unique solution and you would be able to predict data. So this is forward modelling or the forward problem.

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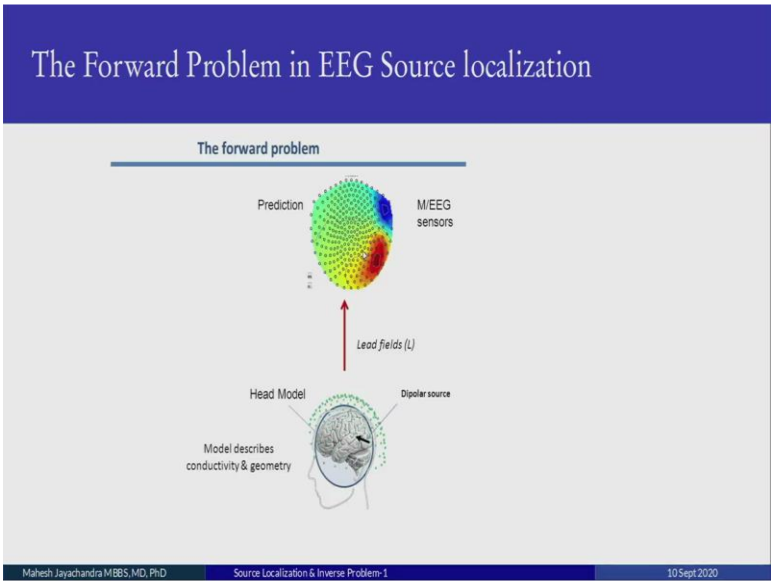

The Forward Problem in EEG Source localization

The forward problem

Prediction

M/EEG sensors

Lead fields (L)

Head Model

Dipolar source

Model describes conductivity & geometry

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So you have your something called head model which describes the scalp, the bone, the meninges, the cerebrospinal fluid and the brain and you have different sensors and then the model also describes the conductivity and geometry of the brain. And you have equivalent dipoles which you can assume occur and then you have a prediction and then with your, how it is supposed to look like and then with your magnetic or electrical easy sensors you can record and see how it looks like. And if there is a discrepancy, you change your model until it fits what is recorded, your prediction fits what is recorded. So this is the forward problem.

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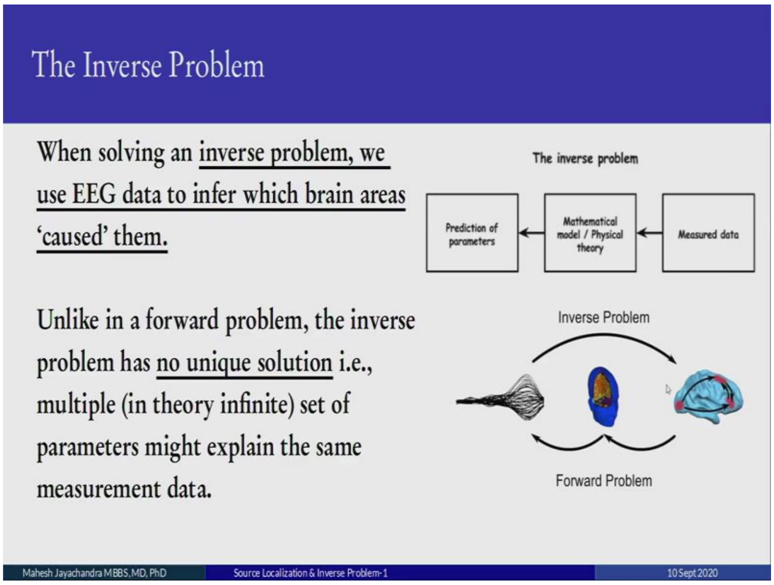

The Inverse Problem

When solving an inverse problem, we use EEG data to infer which brain areas 'caused' them.

Unlike in a forward problem, the inverse problem has no unique solution i.e., multiple (in theory infinite) set of parameters might explain the same measurement data.

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The inverse problem on the other hand is we use EEG data to infer which brain areas caused it. So you have the measured data, it is backward, you have the measured data, your EEG, then you have your mathematical model or physical theory and then you predict the parameters causing it. So unlike the forward problem, there is no unique solution for the inverse problem.

In theory, an infinite number of parameters might explain the same measurement data. For example, you are recording between two areas, two electrodes and you get one. And it could be anything, it could be 5 minus 4, it could be 10 minus 9, 8 minus 7, so on and so forth. There is an infinite possibility, so that is why we do not have unique solution. So what we do is we constrain the solution by using our knowledge of neuroanatomy, neurophysiology.

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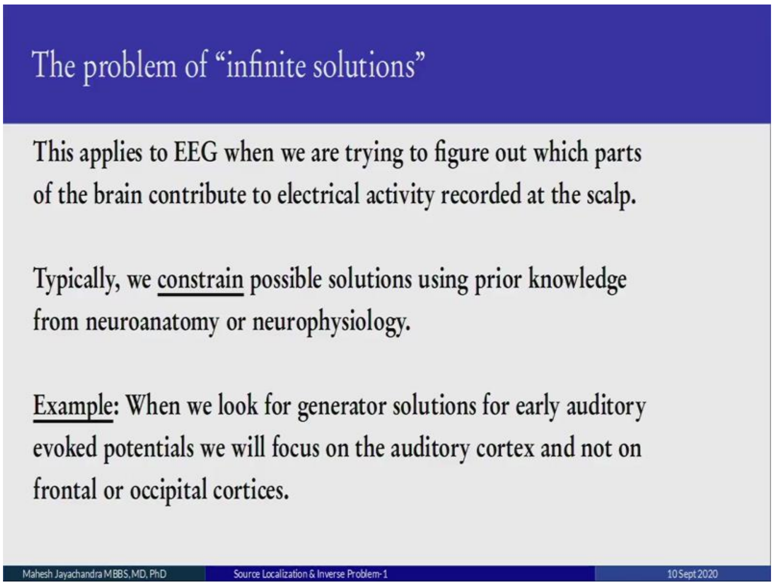

The problem of "infinite solutions"

This applies to EEG when we are trying to figure out which parts of the brain contribute to electrical activity recorded at the scalp.

Typically, we constrain possible solutions using prior knowledge from neuroanatomy or neurophysiology.

Example: When we look for generator solutions for early auditory evoked potentials we will focus on the auditory cortex and not on frontal or occipital cortices.

For example, suppose we have the auditory evoked potential and we have two possible solutions, one in the auditory cortex and one in the occipital cortex. So since we know the anatomy and the physiology we would discard the occipital dipole or the occipital generator and focus on the auditory generator. So this is hardcore physics numerical analysis with help from neuro-anatomy and neurophysiology. And the more number of electrodes you have, the more robust the solution is, so suppose you just have 4 or 5 electrodes compared to 256 electrodes. So the 256 electrode dataset would give you a much better generator solution than just a diminished set of electrodes.

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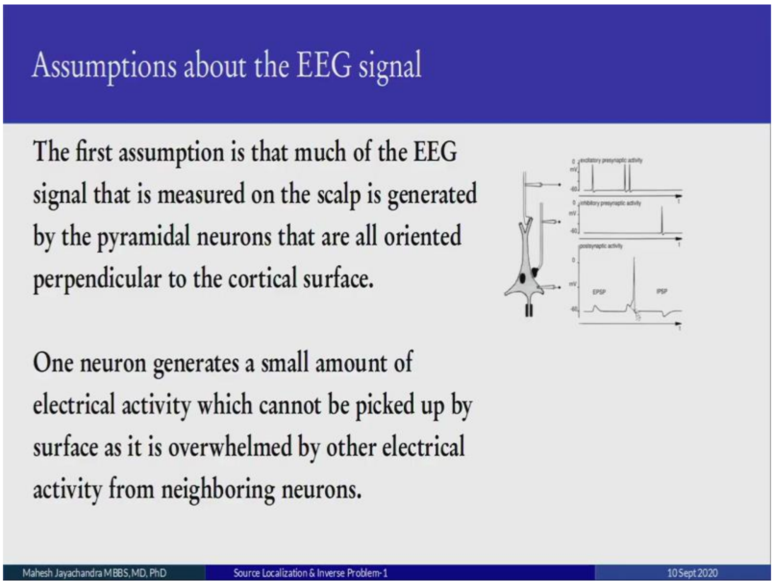

Assumptions about the EEG signal

The first assumption is that much of the EEG signal that is measured on the scalp is generated by the pyramidal neurons that are all oriented perpendicular to the cortical surface.

One neuron generates a small amount of electrical activity which cannot be picked up by surface as it is overwhelmed by other electrical activity from neighboring neurons.

So assumptions. So there are lot of assumptions which we use, the assumption in physics and conductivity and structure. When we are doing the, figuring out the sources and generators of EEG signals in the brain. So the first assumption is that the signal that is measured on the scalp is generated by the pyramidal neurons that are all oriented perpendicular to the cortical surface. And this figure you saw, you encountered earlier, so this is a pyramidal cell. One neuron generates really small bit of activity and it cannot be picked up on the surface because all the other neurons around it they have activity and they overwhelm it especially if they are not synchronized.

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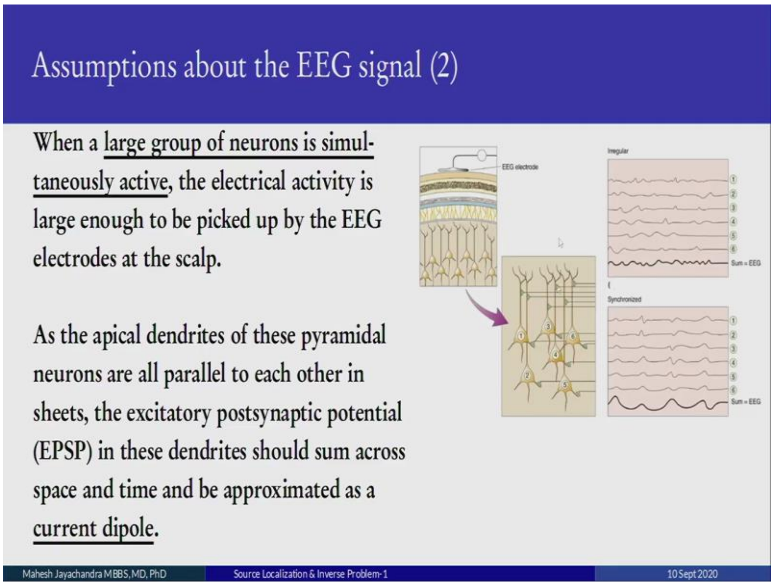

Assumptions about the EEG signal (2)

When a large group of neurons is simultaneously active, the electrical activity is large enough to be picked up by the EEG electrodes at the scalp.

As the apical dendrites of these pyramidal neurons are all parallel to each other in sheets, the excitatory postsynaptic potential (EPSP) in these dendrites should sum across space and time and be approximated as a current dipole.

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But when a large group of neurons is simultaneously active then it becomes an equivalent dipole, you can model it as that, it is a vector with direction and magnitude and the electrical activities big enough to be picked up by the EEG electrode on the scalp. So consider this figure here, you have the electrode over here, this is the scalp, the bone, the meninges, the cerebrospinal fluid and then you have the cortex and then you have the pyramidal cells and layers three, 2, 3, 5 and 6.

So if they are all irregular and they are doing their own thing independently of each other, so you have these different electrical records from each say neuron. The sum is the EEG and it is random. But if all of them are synchronized and they all fire at the same time more or less, then the sum you can see, sum potentials which reflect the summed activity of all these guys firing synchronously. As the apical dendrites of these pyramidal neurons are all parallel to each other, so the EPSP in these dendrites they sum across space and time you have an approximate equivalent dipole which considers the activity of all these neurons.

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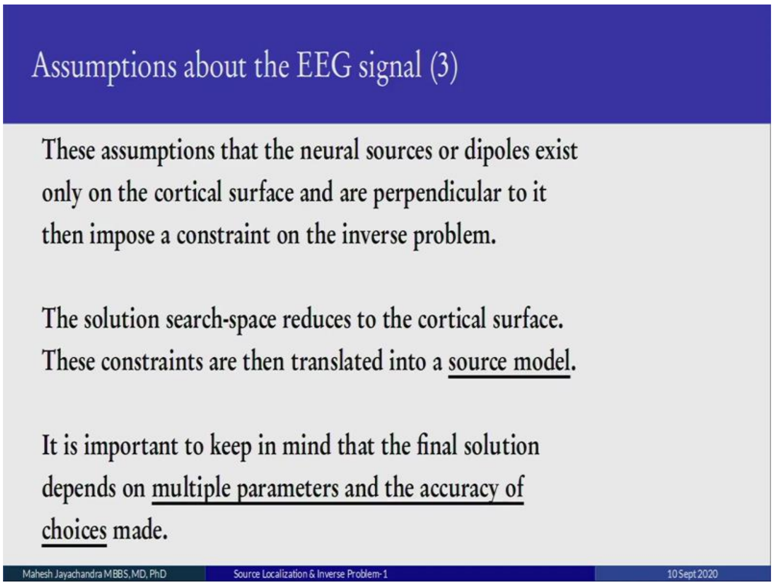

Assumptions about the EEG signal (3)

These assumptions that the neural sources or dipoles exist only on the cortical surface and are perpendicular to it then impose a constraint on the inverse problem.

The solution search-space reduces to the cortical surface. These constraints are then translated into a source model.

It is important to keep in mind that the final solution depends on multiple parameters and the accuracy of choices made.

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So the assumptions of the neural sources or dipoles they exist only on the cortical surface and are perpendicular to it. It then imposes a constraint on the different kinds of solutions you would have for the inverse problem. So the solution’s search space as it were reduces to the cortical surface, you do not have to go inside or outside. And these are then, these constraints are then translated into a source model. It is very important to keep in mind that the final solution that you get, it depends on multiple parameters and the accuracy of the choices made because if the initial conditions or the initial parameters are slightly different then the solution would be very different.

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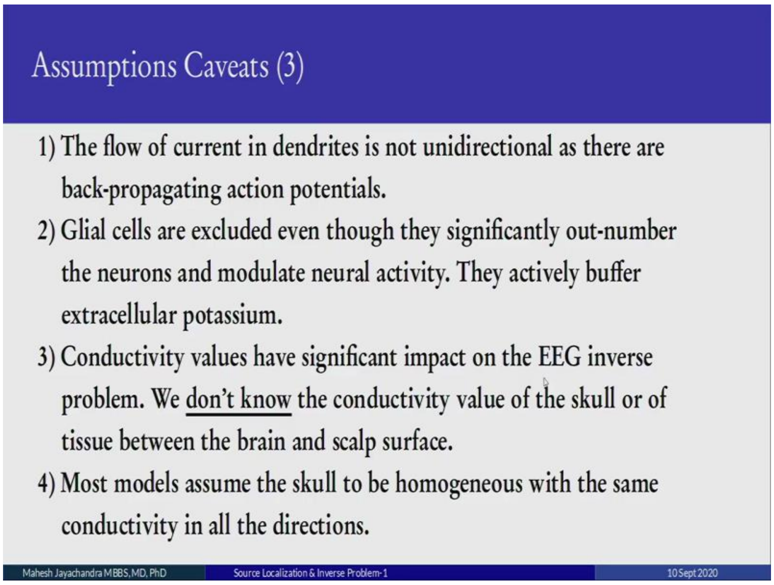

Assumptions Caveats (3)

1) The flow of current in dendrites is not unidirectional as there are back-propagating action potentials.
2) Glial cells are excluded even though they significantly out-number the neurons and modulate neural activity. They actively buffer extracellular potassium.
3) Conductivity values have significant impact on the EEG inverse problem. We don’t know the conductivity value of the skull or of tissue between the brain and scalp surface.
4) Most models assume the skull to be homogeneous with the same conductivity in all the directions.

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So some of the things to keep in mind is we do a lot of simplifying assumptions. We assume that the current in dendrites flows unidirectionally but that is not true because if you remember the action potential starts at the initial segment and it moves forward orthodromic as well as it moves backward and invades soma, the cell body, it is a backpropagating action potentials.

Then there is another whole population of cells which we have not even talked about, those are called glial cells. And these significantly outnumber the neurons and modulate neural activity. For example, they actively buffer extracellular potassium. And if you look at their resting membrane potential, it is near the equilibration potential of potassium. So they are not included in the source models usually.

Then conductivity, so the different parts of the scalp, the coverings of the brain, the scalp, the skull, the meninges, the CSF, all of them have different conductivities. It is not homogenous, neither it is isotropic. So we have to put in numbers for each of these conductivity values. And one big unknown is we do not know the conductivity value of the skull, the human skull even now because whatever skulls we have is usually postmortem and that is not the real situation. And we cannot assume that the postmortem skull’s conductivity is the same as living person’s skull.

And we also do not know, we are not very clear about the conductivity of the tissue between the brain and the scalp surface. Most models assume the skull to be homogenous with the same conductivity in all directions. This is still yet to be proved. So if you have an impedance meter and you access to a neurosurgeon, please get the impedance value of the skull and the tissue between the brain and scalp surface in humans.

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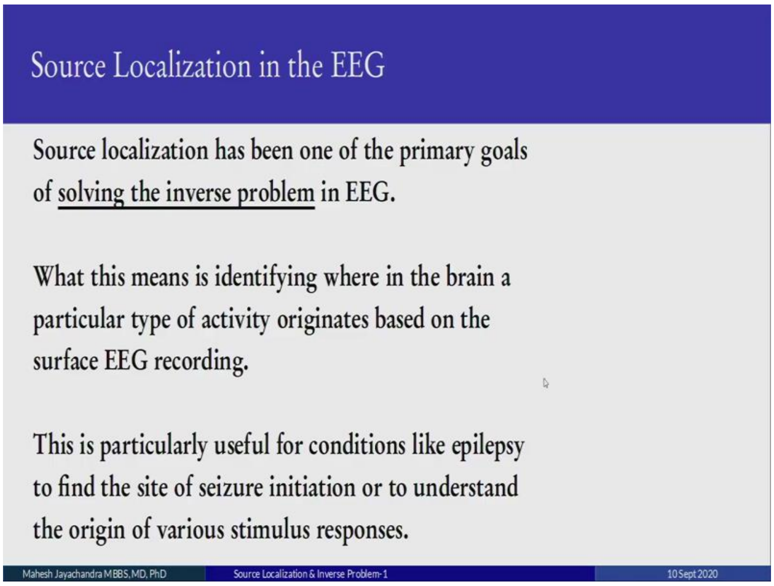

Source Localization in the EEG

Source localization has been one of the primary goals of solving the inverse problem in EEG.

What this means is identifying where in the brain a particular type of activity originates based on the surface EEG recording.

This is particularly useful for conditions like epilepsy to find the site of seizure initiation or to understand the origin of various stimulus responses.

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So source localization in EEG, so has been one of the primary goals to solve this inverse problem. So what this means is identifying where in the brain a particular type of activity originates based on the surface EEG. And this is useful particularly for conditions like epilepsy. Because of epilepsy, the neuron, you have this kind of jerky movement, rhythmic movements very fast and they imply hypo synchronization of pyramidal neurons for example and they all firing together in synchrony. So to be very useful to localize which part of the brain the epilepsy is originating because depending on that, for example, if it is in the temporal lobe and it is temporal lobe epilepsy, the treatment is specific. It can vary for different kinds of epilepsy.

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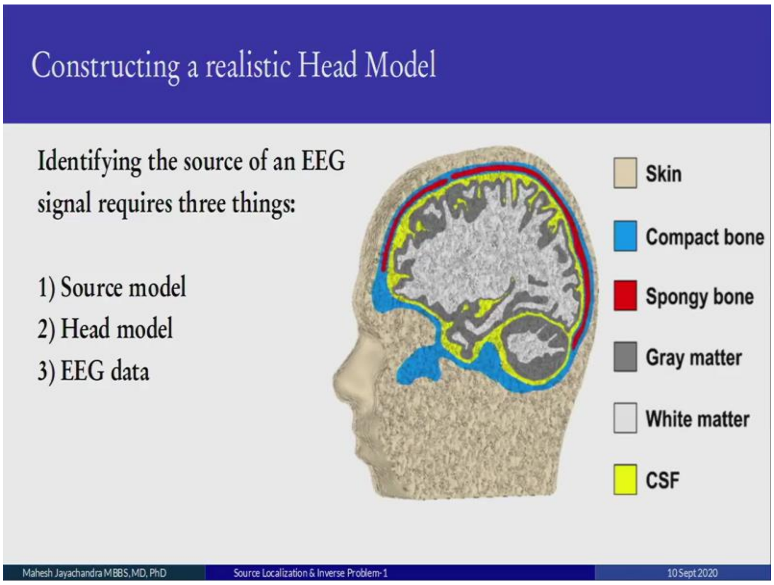

Constructing a realistic Head Model

Identifying the source of an EEG signal requires three things:

1) Source model
2) Head model
3) EEG data

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Now let us get to the nitty-gritty. How do we construct a realistic head model? So to identify the source of an EEG you need three things. One is you need the source model, then you need the head model and then you need the EEG data. And there are different compartments which have to be individually modeled; one is the skin, then you have the bone, compact bone as opposed to spongy bone.

The compact bone is on the outer, inner surface of this skull. The spongy bone is in between. Then of course the gray matter with all its neurons and glial cells and what have you and the white matter which is made up of mostly axons. And the center cerebrospinal fluid. So all these have to be put in to get, to do your source modeling.

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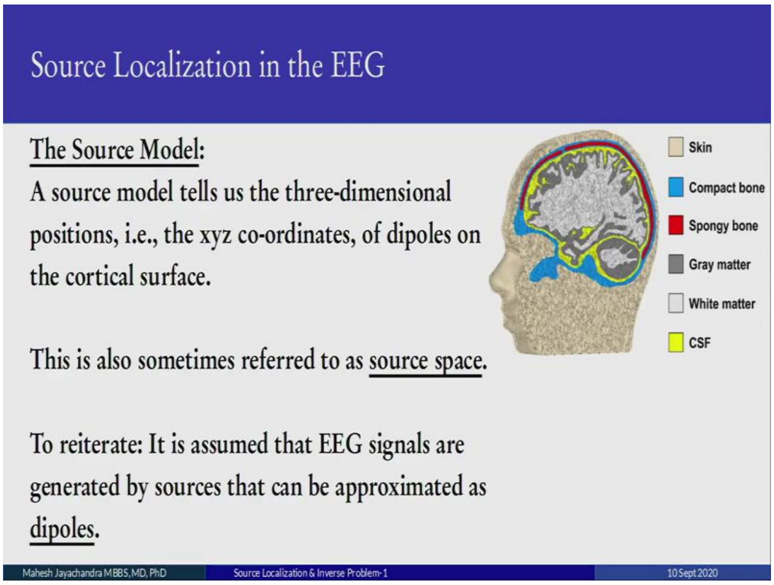

Source Localization in the EEG

The Source Model:
A source model tells us the three-dimensional positions, i.e., the xyz co-ordinates, of dipoles on the cortical surface.

This is also sometimes referred to as source space.

To reiterate: It is assumed that EEG signals are generated by sources that can be approximated as dipoles.

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So the source model. Let us consider the source model first. The source model tells us the three-dimensional positions, that is the x, y, z coordinates of the dipoles of the cortical surface. And this would be over here, over the gray. And this is also referred to as the source space and it is assumed that the EEG signals are generated by sources which can be approximated as dipoles for the reason mentioned earlier.

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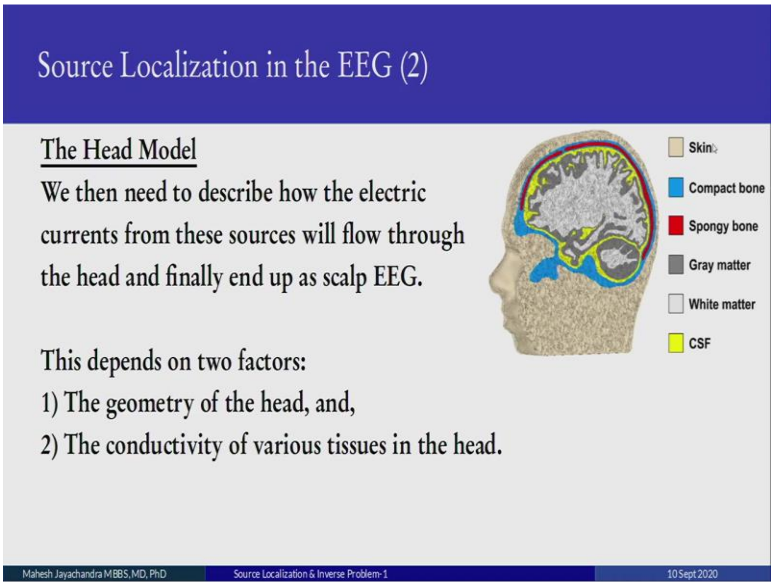

Source Localization in the EEG (2)

The Head Model

We then need to describe how the electric currents from these sources will flow through the head and finally end up as scalp EEG.

This depends on two factors:

1) The geometry of the head, and,

2) The conductivity of various tissues in the head.

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So then we come to the head model. We need to describe how the electrical currents from the sources will flow through the head and finally end up as scalp EEG. So this depends on two factors, one is the geometry of the head and the other factor is the conductivity of the various tissues of the head. So this is skin, compact bones, spongy bone, all these would be involved for the head model.

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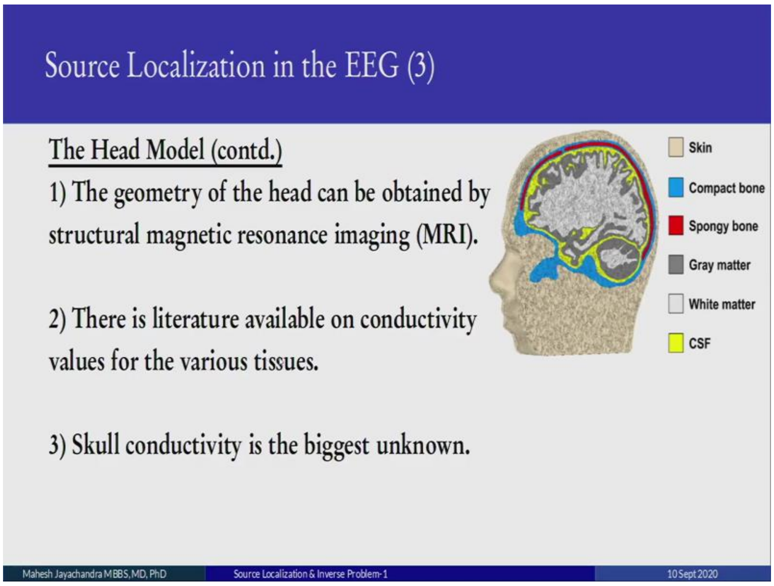

Source Localization in the EEG (3)

The Head Model (contd.)

1) The geometry of the head can be obtained by structural magnetic resonance imaging (MRI).

2) There is literature available on conductivity values for the various tissues.

3) Skull conductivity is the biggest unknown.

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And the head model can be the geometry of the head, can be obtained by MRI, structural magnetic resonance imaging. Not fMRI, just plain all anatomical MRI. Regarding the rest of the tissues there is a huge literature available on conductivity values for the various tissues.

But as mentioned before skull conductivity is the biggest unknown. We have, we assume we do not have any clear experimental data for skull conductivity.