Advances in Additive Manufacturing of Materials: Current status and emerging opportunities

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Lecture 42

I will continue in this lecture on the cranioplasty surgery which I have shown you in the last lecture as how to design the bone flaps for the cranioplasty surgery, what is the importance of the design aspects and so on. I have also mentioned that what are the different materials which can be used for the bone flaps in the cranioplasty surgery. and what are the factors that determine the selection of these different bone flaps and so on. I will continue to show you the video which I have shown and this video essentially is taken at the operation theatre when the patients undergo cranioplasty surgery. this is the last part of the video and you can see the inset in this video, you can see this is the titanium screw and bone plate. bone plate and this is your this is the PMMA that is that PMMA bone flap polymethyl methacrylate bone flap which is mostly used this is done on Indian patients.

property assessment we have measured the strength of this PMMA, it is roughly around 31 megapascal, elastic modulus is around 1.5 gigapascal. And patient specific and anatomically correct implant, so I use this word patient specific anatomically correct implant essentially reduces the total surgery time to less than 2 hours. kind of 90 minutes to 100 minutes or so.

this is just one kind of patient data that you can say that patient 1 to patient 10, this is the age like 29 to 47 years. this data is already published in an open publication and I can also give you the reference of this publications in the subsequent slides. Now, one of the things that I will highlight and then I will explain to you more in details how to determine the clinical outcome analysis and this is called cranial index symmetry. What you see the other data that is provided in this table, what is the defect area? defect area can be as high as 173 centimeter square and this can be as low as 25. the defect area can be 25 to roughly around 175 centimeter square defect area.

this is a large wide variation of the defect area which were reconstructed. We did not mention here what is the complexity of the defects that is another aspects and what is the typical thickness variation of this defect is also important. What is the clinical outcome analysis? Clinical outcome analysis means that how the patient behaves, how the patient performs their physiological functions postoperative after the cranioplasty surgery. what you see here, there are different ways that you can measure the postoperative outcome like one is called eye opening response. This is called Glasgow Coma scale.

eye opening response that is scored between 1 to 4. Then there is something called verbal response that should be scored 1 to 5. Then it is called motor response that is scored 1 to 6. Then these particular things have been mentioned here E3, V4, M5 that means eye opening responses grade 3, range 3, verbal response is 4 and motor response is 5. And cranial index of symmetry I will explain to you very soon that essentially is a quantitative measure and that can be explained by these two slides.

what is cranial and why cranial index of symmetry is very important and how is it measured that I will explain to you in these two slides. For more details you can also see some of these some of the references here. It is 2011 paper by Priscilla, De La Perez and colleagues. multiple surgeries you know the strategies have been used to quantify the extent of symmetry in the human skull and this is also used external medical and dentistry practice and degree of asymmetry in skull might be a function of genetics. conditions during growth, development, disease and defects.

the degree of asymmetry that means as I mentioned to you that human skull is not perfectly symmetric, it is asymmetric

and this degree of asymmetry can be related to genetics or can be related to the conditions during growth or development or diseases and defects. what they use, they use the rudimentary concepts of image processing to quantify symmetry in the skull post-cranioplasty operations. from the CT scan data, multiple slices are taken and these multiple 2-dimensional slices, this is called 2D slices are taken of the skull as seen from the top view are selected and stored in a JPEG format. This image is often resized and modified manual in such a manner that the midline of the skull coincides with the midline of the image that is very important. midline of the skull and midline of the image perfectly coincides and then this transformation to binary image, so to white and black, so white is this skull is colored white and the background is black.

what you see, this is the symmetry, this is the left and this is the right and this is the overlapped one and then when you overlap it, you do notice that there is a place there, it is not perfectly fitting. Although this area fraction of this kind of places is much much less but that is clinically important. The modified image is bisected among along the verticals in 2 images and then CIS is essentially defined as the 2 times the overlapped area divided by total area. overlapped area means what is the area that is being overlapped 2 times because they are overlapping. this is that essentially overlapped area.

This is the overlapped area. And total area means including the area which is not overlapped, okay. This is the total area. And that is traced and calculated and then that is the cranial index of symmetry. it is more clear that you know this cranial index of symmetry should be close to 100% but typically in clinical evidences says that you know most of the cases it is more than 90% or more than 95 is kind of more clinically acceptable and this has done in the patients who received the polymethyl methacrylate implants .

Now, if you go back to this pre and post operative outcome, these are like some of the indexed patients and then what you see, this particular patients, this part of this kind of skull is missing and then if you see that area of the defect, certainly this patient has a much much larger area of the skull is missing, You can see front view as well as the back view. after placing the PMMA implants, you can see this patient has regained this cranium symmetry and then hairs have grown and so on. So, you can still see the signs of the stitches here at this particular region. The same is true for the same patients. The large area of the defect has been reconstructed and this is the area of the skull that where the patient has received these bone flaps.

This young women patients, so this part of the skull that was missing and this particular skull part has been reconstructed during this reconstructive cranioplasty surgery. And these patients were followed up up to 2 years in India. And if you can if you see that more CT scan based analysis of the patients, preoperative this is the axial view clearly in the 2D slices you can see this part of the area in the axial that is what is missing. In the postoperative you can see this axial part has been reconstructed. both in the axial and also the coronal part.

You can see axial, coronal and sagittal part views that you can see that complete reconstruction of these particular defects. it is clear that the patients with varying defect size, they were treated in this reconstructive cranioplasty surgery using polymethyl methacrylate implant and why polymethyl methacrylate? I have mentioned in the last lecture and then perhaps I should reiterate here. that there are other material options like titanium mesh or polyether ether ketone or hydroxyapatite but polymethylmethacrylate is used by far the most extensively. Their clinical evidences are well recorded, are available on open clinical literature And based on the safety and efficacy of this polymethyl methacrylate, we have selected this polymethyl methacrylate. And in our clinical study, I have shown that is at least on the 20 patients with different cranial defect size could be reconstructed using polymethyl methacrylate implant with reasonably good clinical outcome score.

some of the typical cases I will explain to you now. for example, this is kind of going towards the last phase of this lecture. I reiterate that we need to have customized bone flaps because you remember one of the statement that I made in the last lecture is that one size does not fit all. What it means that you cannot have you cannot have or you cannot afford to know that this particular bone flaps of a particular area and thickness can fit the patients. Even if that there is different sizes of this bone flaps are available but the patients who will be treated for this cranial plastic surgery, often they have

complex cranial defect morphology in terms of the shape, contour and thickness of the defect.

Just to substantiate what I am saying, for example, I will show you in one of the subsequent lecture on the 3D printing of the dental implants, there I will show you the dental implants are always available in different sizes. For example, 3.7 millimeter diameter, 10 or 12 millimeter length or 4.2 millimeter diameter in different length.

4.7, 5.2 and so on. therefore, these sizes are manufactured by the dental implant manufacturer and a prosthodontist or dental surgeon has the access to different sizes of this dental implants. Whenever they want to use it they based on the CBCT cone beam convergent tomography or you know about the CBCT images and so on. They can find out that what is the implant they need for the surgery and once that implants that they need they find it then they can essentially find out that this particular patients will require let us say 4.2 millimeter diameter and 10 millimeter height for example. And then you can take that implant from the implant suit along with accessories and then you can place the implant for the treatment of the tooth loss which clinically is termed as edentulism.

But that is not the case in the cranioplasty surgery that is what I am trying to emphasize that you, for example, in the last slide I have shown you that what is the defect size,. this varies from 25 to roughly around 175 centimeter square. but their size is not a regular size it is not a rectangular size or it is not a triangular shaped size and so on a manufacturer cannot manufacture these bone flaps with a range of sizes and can supply to the hospitals particularly the neurosurgeons that these are the range of sizes and most of the patients their cranial defects will fall in the sizes and you can safely use these sizes. No, that approach will not work. We must have customized bone flaps.

And that is the reason a patient has to come back to the hospitals for the CT scan or MRI scan and to be sent to the designer or manufacturer to make these customized bone flaps, And this entire process actually follows these things that you have a frontal view, lateral view, superior view and those views are to be very very carefully investigated and then that will allow you to particularly design the bone flaps and these bone flaps are to be casted and then this will be ETO sterilized, ethylene oxide sterilized before it can be placed in the patients. And polymethylmethacrylate is a FD approved material. , this is kind of clinically acceptable material. Now, also one of the things that we have found out that in the patients who has younger patients and also the longer time gap between the decompressive craniectomy and cranioplasty surgery. Because you remember the first step in the treatment of the brain tumor or the traumatic brain injury is the decompressive craniectomy.

decompressive craniectomy means some part of the cranium is surgically cut to manage the intracranial pressure ICP and this intracranial pressure temporarily stabilize the patient's activity before the patient undergoes cranioplasty surgery and that is a reconstructive procedure that means in this part whatever cranial defect is cut so that cranial defect part is reconstructed by using this bone flap. Now, what I am saying is that there is a time gap between decompressive craniectomy and cranioplasty surgery. And this time gap if it is longer time gap in younger patients, so there are greater chances that physiological bone remodeling can take place. I use the term physiological bone . So, this physiological bone remodeling when it takes place, then the defect size remains not the same as immediate post decompressive craniectomy and to the preoperative pre cranioplasty operation.

You understand these two time gap there is a physiological bone remodeling takes place and therefore the design of such defects even is more challenging. and that younger patients and the large gap between the decompressive craniectomy and cranioplasty surgery, these are the patients, their designing stage needs more careful attention so that physiological bone remodeling aspect can be improved. considered very carefully and those patients are also being treated in that total patient cohort of 20 patients, 10 patients in Bangalore, 10 patients in Wardha and their average cranial index symmetry is close to 95% and Glasgow outcome score is kind of 4.2 +9. these papers that one of the review paper we published in Acta Biomaterialia in 2022 and Journal of Clinical Neuroscience that is one review paper 2021 and Journal of Biomaterial Applications in 2024.

And this particular work was done in collaboration with a team of neurosurgeons and cranio maxillofacial surgeons in two different hospitals, Ramaiah Medical College and Duttameghe Institute of Medical Sciences and also several young researchers were involved. They are also trained on this clinical relevance aspect, but they did all the design aspects, they did the 3D printing of the cranial model, they were manufacturing this bone flap using the conventional casting technique, then they were sending to the clinicians. And in between they are in constant touch with the clinicians to see that the design file is expected to serve the purpose in terms of the completely fitting the cranial defects and so on. these particular two studies in two different hospitals were very helpful to train the next generation researchers in this particular cranioplasty surgery or more generally in the translational research and they also greatly benefited by participating in this clinical studies. this brings me to the two lectures where I have shown that how 3D printing and design are helpful to manufacture customized bone flaps for patient care.

And patient care in this particular case, the patients who have undergone decompressive craniectomy and cranioplasty surgery and these entire study were done in India in two different hospitals after obtaining necessary institute human ethics committee approval, hospitals ethics body approval and clinical trial registry of India registration and then all other regulatory clearances. Thank you very much.