Comparative study of the circumferential and volumetric analysis between conventional casting and three-dimensional scanning methods for transtibial socket: A preliminary study

W Mehmood, NA Abd Razak, MS Lau, TY Chung, H Gholizadeh and NA Abu Osman

Abstract
Transtibial prosthetic sockets can be fabricated either by the conventional way, which involve using plaster of Paris bandages for casting. This will include modifications through hand, scanning and digital imaging of software. The aim of this study is to determine the circumferential profiles and conduct a volumetric analysis of a conventional socket that has fabrication using biosculptor technology. In doing this, a male transtibial amputee, age 28 years old with stable health condition was studied, where circumferential measurements were taken at intervals of 1 cm from the distal end of the residual limb to the medial tibial plateau level. Furthermore, the interior volume of both sockets and residuum were determined directly using water displacement method. A comparative value for the calculation of volume was also carried out using engineering mathematical equations. From these measurements, a total surface bearing transtibial sockets was fabricated to compare the changes of circumferential values of both sockets. The finding shows a percentage of the difference between the volume of the residual limb and conventional sockets to be 6.09%, whereas the biosculptor fabrication socket was 7.84% using the water displacement method. A comparison of circumferential profiles and volumetric analysis findings on the contrary showed that socket fabricated using the biosculptor technology is interchangeable with the conventional socket with more advantages, where biosculptor technology produces cheaper sockets and faster process with digital function in the procedure, unlike the conventional manual technique.

Keywords
Socket, biosculptor, Computer Aided Design, Computer Aided Manufacture, prosthetic, volumetric, residual limb

Date received: 7 June 2018; accepted: 15 October 2018

Introduction
The transtibial residuum contains two bones (tibia and fibula), making it challenging to fabricate a well-fitted socket. The important part is to provide relief to the bony structure and give pressure on the tolerant areas which help in fabricating good comfortable sockets. This is followed by a precise modification because a little bit of pressure around the sensitive areas of the residuum will result in discomfort for the amputee when walking. Thus, when applying force during the modification, it is necessary to have a balance of pressure and relief points on the model. This is because, if there is a mismatch in the pressures and relief is applied on the...
residuum, it will not provide optimum fitting but discomfort and pain on the residuum. Until now, there has not been any scientific evidence on how to modify a cast using the conventional method of casting with plaster of Paris (POP) bandage and modification by filling it with POP powder using a Surform blade. However, it is important to have an alternative method where there is a scientific evidence on how to modify the cast using numerical values. In view of this, the use of a Computer Aided Design and Computer Aided Manufacture (CAD-CAM) can provide one of the precise methods that can literally see and record measurements for modifying the cast. Generally, socket fabrication using the conventional method usually follows subjective experience and skill for modifying the model. Conversely, sockets made using CAD-CAM take less time, thereby improving the work speed in fabricating more sockets in less time. This helps the process of modifying the model digitally using software with more accuracy and precision. Therefore, the induction of CAD CAM has revolutionized the concept of modification and creating sockets precisely. This is credited to the technology that has played a vital role in improving the accuracy of fabricating sockets and improving the quality of life of the amputees using the sockets fabricated through technology. Based on this, the present research focuses on methods to ease the process of fabricating well fitted sockets with cheaper price. Biosculptor technology is a three-dimensional (3D) CAD-CAM technology for fabricating transtibial sockets. Its procedure starts with scanning the residual limb using a 3D handheld bioscanner for taking the impression of the residuum through the use of an infrared light that sweeps on different parts of the residuum with the help of a digital image. After this, the model is then sent to a modification software known as bioshape, which helps in making the necessary modifications following the measurements recorded from the amputee. The final model is then printed using biennial to carve the model through a milling machine. Conventionally, this method is simple, that uses POP bandages to take the impression of the residuum to produce a negative cast. This will then be followed by a negative cast to fill using POP powder whereby modification will be done according to the measurements. The model will then be rectified following the measurements that would be recorded on the residuum. The aim of this study is to compare the circumferential and volumetric analysis between sockets fabricated using biosculptor technology and the conventional method. This is believed to help to convince the clinician to shift the central fabrication from conventional to modern technology, which will not only help in time and cost reduction but also improve the quality of the patient’s life.

Materials and methods

The first criteria taken into consideration in this research are the circumference measurements to determine the residuum volume. The accuracy and precision of the technique to assess residual limb volume was checked using a measuring tape. The evaluation of the method was done by approximating the residuum due to several cut cones from the circumferential measurements. The second consideration of this study is to assess the volume of the sockets fabricated. Based on these, three methods were demonstrated to determine the volume, which are (1) direct water displacement method, (2) two indirect methods using frustum sign model and (iii) disc model. In this study, a 28-year-old male amputee with bilateral transradial and unilateral (left) transtibial amputation was recruited as the subject for this pilot study as shown in Figure 1. The cause of his amputation was due to an electrical shock; thus, there were severe scars...
on the upper and lower limbs. The shape of the residuum was considered to be cylindrical with soft tissue consistency.

This research is conducted with the approval by the National Medical Research Register Secretariat 37912, under the guidance of Certified Prosthetist and Orthotist (CPO) ISPO CAT 1 (refer to Appendix 1). Also, a prior consent was taken from the subject used in this research, of which his consent letter can be referred in Appendix 2.

**Experimental setup**

The different points that were marked for conventional casting on the patient residuum include patella, patellar tendon, anterior tibial prominence, tibial tuberosity, fibular head, tibial crest, lateral tibial border, medial tibial border, hamstring tendons, fibular end and tibial end. A POP bandage was used to take the impression of the residuum. The cast obtained was filled using POP powder to get the positive model to be modified as shown in Figure 2.

In addition, scanning was done to obtain the impression of the residuum using the bioscanner which is a 3D handheld tool that has a built-in dual camera at $45^\circ$ angle to each other, including a slot for laser light in the middle. The laser light strikes on the residuum to take different sweeps in getting a full scan of the residuum. The 3D model was modified in the bioshape software which is a CAD software designed specifically for the clinician to make adjustments and modifications in the computer after the scanned image is obtained, that helps in attaining the desired adjustments needed in the model. Also, the scanned image was modified according to the measurements, and the model was shaped by adding the bony prominences, including a removal on the pressure tolerant areas of the model. These changes were done according to the shape of the residual limb. From above, a positive model was obtained using biomill as shown in Figure 3. Biomill is a milling system which provides the final 3D model by carving it through a high-speed spindle attached to the system. The polyurethane foam and biomill as placed in the system help in cutting it according to the shapes and contours sent from bioshape software (Figure 4).

**Circumferences and volumetric analysis**

A circumferential measurement was carefully located at 1-cm interval. This is followed by a specific interval that was laid out from bony landmarks to be defined accurately during the plaster casting procedure as shown in Figure 3.

In addition, a length measurement was accurately gauged from the distal tip end of the residual limb to both the medial tibial plateau and to the inferior edge of the patella until the supracondylar (SC) wedge level.

**Volume: water displacement method.** With regard to this, the residuum was placed into a bucket of water slowly until the SC wedge level; water could flow out from the bucket and stop by itself as seen in Figure 5. Then, water displaced was measured using a measuring cup to obtain the volume in cubic centimetres ($\text{cm}^3$). This procedure was repeated 10 times to get the average value (Figure 6).

The interior volume of both sockets was measured by filling up water in the socket up to SC wedge level. The amount of water displaced was then transferred into measuring cup to obtain the volume in cubic centimetres ($\text{cm}^3$). Again, this procedure was repeated 10 times to get the average value.

**Disc model method.** The residuum of the subject was assumed to be made up of discs with 1-cm height. Based on this, the measured values of circumferences were inserted into the formula
Figure 3. (From left to right) Marking of the 1-cm interval made, scanning the stump using bioscanner and model modified using bioshape.

Figure 4. (From left to right) Biosculptor mould, conventional mould and the comparison of models.

Figure 5. Measuring stump volume using water displacement method.
\[ V = \sum \left( \frac{C^2}{4\pi} \times h \right) \]  
where \( C \) = circumference at each level (cm), \( h \) = height of each disc (cm), \( \Sigma = \) sum of discs at each level (cm³) and \( V \) = volume of residuum or socket (cm³).

**Frustum sign model method.** The residuum was assumed to be a truncated cone (frustum) of 21 cm. As a result, the measured values of circumferences were inserted into the formula

\[ V = \frac{\pi}{12\pi^2} \times h(C^2 + Cc + c^2) \]  
where \( C \) = circumference of the uppermost disc of the residuum (cm), \( c \) = circumference of the lowermost disc of the residuum (cm), \( h \) = total length of the residuum up to SC wedge level (cm) and \( V \) = volume of residuum or socket (cm³).

**Integral of graph method.** The method employed here is to calculate radii using the values of circumference measured at each level. A graph of radius versus length was plotted for residuum (biosculptor fabricated socket and conventional socket) as shown in Figure 7. A polynomial equation for each plotted line was generated using Microsoft Excel. The integration of the polynomial equation obtained around the area under the graph and rotation along the X-axis were used to obtain the volume of the residuum and inner volume for both sockets.

### Circumferential profile

1. Measurements of the length and circumference of the residuum are tabulated, in which the percentage of differences in each circumferences level were calculated using equation 3

\[ \text{Percentage of differences in circumference} \times 100\% = \frac{\text{Socket circumference (cm)} - \text{Stump circumference (cm)}}{\text{Stump circumference (cm)}} \times 100\% \]  

2. A graph of circumference versus the length of the residuum was plotted to observe the relationship and differences for both sockets.

3. The mean percentage of difference in each circumference between both sockets was calculated using equation 4 as follows

\[ \text{Mean percentage of difference in circumference} \times 100\% = \frac{\text{Sum of percentage of difference in circumference}}{\text{Total data}} \times 100\% \]
Volumetric analysis

1. The mean volume of the residuum, and both sockets calculated for water displacement method, the disc model method, the frustum sign model method and integral of the graph are tabulated as shown in Tables 3 and 4.

2. The percentage differences in volume for both sockets compared to the residuum were calculated for all the four methods using equation 5

\[
\text{Percentage of differences in volume } (\%) = \frac{\text{Volume of socket} (\text{cm}^3) - \text{Stump volume} (\text{cm}^3)}{\text{Stump volume} (\text{cm}^3)} \times 100\%
\] (5)

i. Value of ‘y’ is derived from Figure 7, where line of graph

\[
y = (7E - 05 \times 2 + 0.0675x + 4.6913)
\] (6)

(a) The mathematical calculation in the integral of graph method to obtain volume is as follows

1. Radius at each 1-cm interval of residuum was calculated using equation 7

\[
r = \frac{C}{2\pi}
\] (7)

where \( C \) = circumference at each level (cm)

2. Integration of the equation along X-axis is done using equations (8)-(10)

\[
\delta V = \text{Area under the graph} \times \delta x
\] (8)

\[
V = \int_a^b \text{Area under the graph} \times dx
\] (9)

where \( dx \) = length of residuum

\[
= \int_1^{21} \pi r^2 dx
\]
where $r = y = \text{equation of the line graph}$

$$= \int_{1}^{21} \pi y^2 \, dx$$

$$= \pi \left[ \int_{1}^{21} y^2 \, dx \right]$$

(10)

Calculation of the volume of residuum using the above method

$$V = \pi \left( \int_{1}^{21} (7 \times 10^{-5} x^2 + 0.0675x + 4.6913)^2 \, dx \right)$$

$$= \pi \left( \int_{1}^{21} (\frac{4.9 \times 10^{-6} x^4 + 9.45 \times 10^{-6} x^3 + 0.00521 x^2 + 0.6333x + 22.01}{5}) \, dx \right)$$

$$= \pi \left( \int_{1}^{21} \frac{4.9 \times 10^{-6}}{5} x^5 + \frac{9.45 \times 10^{-6}}{4} x^4 + \frac{0.00521}{3} x^3 + \frac{0.6333}{2} x^2 + 22.01 \, dx \right)$$

$$= \pi \left( \frac{618.38 - 22.647}{5} \right)$$

$$= 1871.79 \text{cm}^3 (5 \text{ sig. f})$$

3. The calculation was repeated for inner volume of biosculptor fabricated socket and conventional socket.

**Results**

The data obtained from the subject of this study were analysed in two parts (circumferential profile and volumetric analysis). The circumferences were analysed before and after the modification procedure. The modification procedure includes both manual modification of the POP model and the modification of the biosculptor technology using bioshape software. In order to conduct volumetric analysis, four methods of calculation were carried out on both sockets, in which a comparison was made with the residuum.

**Discussion**

Figure 8 shows the graph of the circumference at each 1 cm of interval, starting from the distal tip end of the residuum, and all the way up to the SC wedge level. At the beginning (most distal end), bioscanner scanned image had the circumferences, nearer to the residuum compared to the POP cast. At the middle of the residuum (between 4 and 12 cm), circumferences measured by the bioscanner scanned image deviate more from the residuum compared to the POP cast, having larger values than the residuum. Conversely, both POP cast and bioscanner scanned image have their measurement near to the residuum at 12–17 cm. However, a further deviation was observed at the proximal end after 17-cm measurements from the bioscanner scanned image to the residuum, thereby making the values to be larger compared to the POP model. Comparisons can be made to the findings derived in this study from the circumferential profile with the research conducted by Öberg et al., on CAD CAM and conventionally fabricated sockets. It was discovered that the finding of the close circumferential profile for both socket fabrication is similar to that of this study. However, this study does not include judgement by subjective feedback from the users, as it was presented by the researchers. Hence, the sockets in this study are only considered as satisfactory in terms of socket circumferential profile.

As shown in Table 1, the mean percentage of circumference difference (between bioscanner scanned image and residuum) is 2.9%, whereas that of POP cast is 1.2%. It was also discovered that the bioscanner made a higher error in casting procedure compared to the POP bandage casting technique. But the POP cast has the larger circumferences than the residuum at the distal end. The reason for this condition may be due to the expansion of the negative cast during the filling process. In the middle, the bioscanned image has a greater deviation from the residuum measurements. While at the distal end, the deviation of bioscanned image is the greatest compared to the POP cast that appeared to be smaller than the residuum. One reason that is believed to cause this condition is the extra force given during the casting procedure using POP bandages (pulling the bandages too tight), thereby causing the negative cast to become smaller in size. Figure 9 shows the graph of the inner circumference at each 1 cm of interval, starting from the distal tip end of the residuum up to the SC wedge level for both conventional and biosculptor fabricated sockets, including a required measurement that was plotted as control. In observing the beginning (1–6 cm) of the graph, the inner circumferences of the

<table>
<thead>
<tr>
<th>Mean percentage of circumference difference (%)</th>
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</thead>
<tbody>
<tr>
<td><strong>Bioscanner scanned image</strong></td>
</tr>
<tr>
<td>2.89</td>
</tr>
</tbody>
</table>

POP, plaster of Paris.
Figure 8. Circumference at each 1-cm interval of length for stump, POP cast and bioscanner scanned image before modification.

Figure 9. Circumference at each 1-cm interval of length for desired measurement, conventional socket and biosculptor fabricated socket after modification.
biosculptor fabricated socket were nearer to the control when compared with the conventional socket. On the contrary, towards the middle (between 6 and 13 cm), the inner circumferences of the biosculptor socket were slightly smaller than the control. The conventional socket has a closer value to the control but between 11 and 15 cm, the measurements of the biosculptor fabricated socket deviate far from the control, leading to small values. Whereas the conventional socket has its inner circumferences close to the control but slightly smaller. At the proximal end (between 15 and 18 cm), inner circumferences of the biosculptor fabricated socket was found to be the same as desired measurements. However, values of conventional socket deviate to smaller values. Table 2 shows the mean percentage of circumference difference of biosculptor socket that is 0.59% and 0.60% for conventional socket when compared to the required measurement. The degrees of error for both sockets were approximately equal and the values are small when compared to the mean percentage of difference in circumference during the casting procedure. Despite some errors during the casting procedure, biosculptor technology was still able to produce an identical socket as the conventional one with more advantages, such as lower cost and less time consumption. Sanders et al. have demonstrated that out of 33 sockets fabricated using CAD-CAM technology, 23 required modifications. Figure 9 shows the close relationship between the two sockets but there are still some irregularities and deviations from the required measurement. The soft feature of the measuring tape itself may cause the systemic error when it was improperly bounded on the inner surface of the socket. Tables 3 and 4 show the percentage of inner volume difference for the biosculptor fabrication and conventional socket when compared to the residuum. Negative values of the percentage show that the data are on the right path. This is because, for every socket fabricated, it must be modified to fit the residuum. Hence, the inner volume of both sockets must be smaller than the volume of the residuum. In this study, the four methods used to assess the residuum volume gave different values of percentage difference. Using the water displacement method, the biosculptor socket has a larger difference (−7.4%) than the conventional socket (−6.09%). The disc model method gave the close percentage of difference for both sockets, approximately −3.6%. The frustum sign model method showed that the conventional socket gave a larger percentage of −3.5% compared to the biosculptor fabricated socket which is −1.5%. Even though this value is smaller, it looks more like an outlier in this data group because the range of error for all the three indirect methods lies between −3% and −4.1%. This discovery is found to be similar to the research conducted by Sukul et al. In this study, a close correlation between the water displacement method and disc model method has been concluded, but the frustum sign model is not applicable. An observation of the percentage of volume difference, using integral of graph method, shows that the biosculptor fabricated socket made a higher percentage of difference (−4.1%), whereas the conventional socket was −3.6%. However, due to the loss of both upper limb of the subject, it increased the difficulty and inaccuracy of the measuring procedure because the subject was unable to cooperate fully. Table 2. Mean percentage of difference in inner circumference of biosculptor fabricated socket and conventional socket compared to the required measurement after modification.

<table>
<thead>
<tr>
<th>Mean percentage of circumference difference (%)</th>
<th>Biosculptor socket</th>
<th>Conventional socket</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.59</td>
<td>0.60</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Percentage of inner volume difference between biosculptor fabricated socket and residuum using water displacement method, frustum sign model and integral of the graph.

<table>
<thead>
<tr>
<th>Method</th>
<th>Residuum (cm³)</th>
<th>Biosculptor fabricated socket (cm³)</th>
<th>Percentage of difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water displacement</td>
<td>1916.67</td>
<td>1766.43</td>
<td>−7.84</td>
</tr>
<tr>
<td>Disc model</td>
<td>1967.61</td>
<td>1897.45</td>
<td>−3.57</td>
</tr>
<tr>
<td>Frustum sign model</td>
<td>1865.35</td>
<td>1837.25</td>
<td>−1.51</td>
</tr>
<tr>
<td>Integral of graph</td>
<td>1871.79</td>
<td>1795.35</td>
<td>−4.08</td>
</tr>
</tbody>
</table>

Table 4. Percentage of inner volume difference between conventional socket and residuum using water displacement method, frustum sign model and integral of the graph.

<table>
<thead>
<tr>
<th>Method</th>
<th>Residuum (cm³)</th>
<th>Conventional socket (cm³)</th>
<th>Percentage of difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water displacement</td>
<td>1916.67</td>
<td>1800.00</td>
<td>−6.09</td>
</tr>
<tr>
<td>Disc model</td>
<td>1967.61</td>
<td>1896.27</td>
<td>−3.63</td>
</tr>
<tr>
<td>Frustum sign model</td>
<td>1865.35</td>
<td>1799.12</td>
<td>−3.55</td>
</tr>
<tr>
<td>Integral of graph</td>
<td>1871.79</td>
<td>1805.02</td>
<td>−3.57</td>
</tr>
</tbody>
</table>
was unable to stabilize during standing.\textsuperscript{19} Also, the flow of water out of bucket required a period of time that increased the difficulty of the subject to stabilize with one of the flexed standing leg, in order to lower his resi- duum into the water bucket.\textsuperscript{21,22} This pilot study shows availability of many methods to determine the volume of stump and sockets. From the percentage of difference in each method, it can be said that the disc model method and integral of graph method to obtain volume are applicable. Effort in studying the application of the frustum sign model method needs to be further carried out. However, the water displacement method to measure stump volume was accepted as the most accurate method in this study. Although the water displacement method has an advantage of direct measurements, still it is time-consuming for measuring the volume, including the fact that it is not applicable to the patient after immediate postoperative period.\textsuperscript{20}

**Conclusion**

Findings from the circumferential profile and volumetric analysis in this study have shown that the biosculptor technology is able to work as the conventional method to fabricate a transtibial socket, but this technology will only work in its optimum and most efficient with the condition that the user has the knowledge in the prosthetic and orthotics field. Even though the scanning process of the residual limb can be easily done using bioscanner, the modification process and bioshape manipulation software, it still requires theoretical understanding and practical experience to complete proper modifications to the digital image. Both time and cost savings are the advantages of the biosculptor technology as found in this study. It was also discovered that, it is not necessary to use POP bandages during casting because the digital image can be used instead in order to conduct unlimited scanning trials. In this study, during the modification stage, usage of POP powder was eliminated. This is believed to help in saving the cost as well as saving the environment due to the POP solid waste that was reduced. Another reason is that, the POP is a material that takes a long time to decompose and it is not environmentally friendly. Also, in this study, a comparison of circumferential profiles and volumetric analysis showed that socket fabricated using the descriptor technology is interchangeable with the conventional socket. Hence, the biosculptor technology method is comparable with the conventional method. It is an applicable technique in the fabrication of prosthetic transtibial socket with the condition that the user is a professional in the prosthetic and orthotics field.

**Declaration of conflicting interests**

The author(s) declared no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

**Funding**

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This study was supported by the Malaysia UM/PPP/PG208-2016A.

**References**


**Appendix 1**

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*UNIVERSITY OF MALAYA*

Department of Biomedical Engineering (Prosthetics and Orthotics)

**Patient/ Participant Consent Form**

I hereby take part on a voluntary basis for the purpose of learning for KUEP ___________ course which is held on the (date) ___________ . I understand the description of the procedures that have been explained by the demonstrator/student and agreed to authorize the process of clinical examination, fabrication and fitting of orthosis/prosthesis on myself. I also give permission to the demonstrator/students to use my personal information, pictures or videos for learning and educational purposes.

Participant’s name: ___________

IC number : ___________

HP number : ___________

Signature : ___________
Appendix 2

<table>
<thead>
<tr>
<th>NAME OF ETHICS COMMITTEE/HR</th>
<th>MREC ID NO.</th>
</tr>
</thead>
<tbody>
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<td>Medical Research Ethics Committee, University Malaya Medical Center</td>
<td></td>
</tr>
<tr>
<td>ADDRESS: BERSIH PANTAI 36000 KUALA LUMPUR, MALAYSIA</td>
<td></td>
</tr>
<tr>
<td>PROTOCOL NO.(if applicable):</td>
<td></td>
</tr>
<tr>
<td>TITLE:</td>
<td></td>
</tr>
<tr>
<td>PRINCIPAL INVESTIGATOR:</td>
<td>SPONSOR</td>
</tr>
</tbody>
</table>

The following items [✓] have been received and reviewed in connection with the above study to conducted by the above investigator.  

- Application to Conduct Research Project(s)  
  - Var.No:  
  - Var.Date:  

- Study Protocol  
  - Var.No:  
  - Var.Date:  

- Patient Information Sheet  
  - Var.No:  
  - Var.Date:  

- Consent Form  
  - Var.No:  
  - Var.Date:  

- Questionnaire  
  - Var.No:  
  - Var.Date:  

- Investigator's CV / GCP (Wajid, Musamud, Dr. Norul Amal Bin Abu Rashid)  
  - Var.No:  
  - Var.Date:  

- Insurance certificates  
  - Var.No:  
  - Var.Date:  

- Other documents  
  - Var.No:  
  - Var.Date:  

And the decision is [✓]  

- Approved (Full Board)  
- Approved (Expedited)  
- Rejected (reasons specified below or in accompanying letter)  
  
Comments: 

The investigators are required to:  
1) follow instructions, guidelines and requirements of the Medical Research Ethics Committee.  
2) report any protocol deviations/violations to Medical Research Ethics Committee.  
3) provide annual and closure report to the Medical Research Ethics Committee.  
4) comply with International Conference on Harmonization – Guidelines for Good Clinical Practice (ICH-GCP) and Declaration of Helsinki.  
5) obtain a permission from the Director of UMMC to start research that involves recruitment of UMMC patient.  
6) ensure that the research is sponsored, the usage of consumable items and laboratory tests from UMMC services are not charged in the patient’s hospital bills but are borne by research grant.  
7) note that he/she can appeal to the Chairman of Medical Research Ethics Committee for studies that are rejected.  
8) note that Medical Research Ethics Committee may audit the approved study.  
9) ensure that the study does not take precedence over the safety of subjects.  

Date of meeting:  
Date of approval:  

This is a computer generated letter. No signature required.