This study investigates the fabrication of a female reproductive biomodel with the aid of stereolithography. It was undertaken to determine the dimensional accuracy of the biomodel derived from spiral computed tomography and fabricated using the rapid prototyping technique of stereolithography. Distance measurements were taken to compare the resulting biomodel with the original organs. Fourteen measurements were taken by three different observers for objectivity and accuracy. The 160 gram biomodel is slightly more voluminous than the original organs with a mean difference of 1.73 mm and a standard error of 0.86 mm. The average positive difference is 1.955 mm with a standard error of 0.82 mm. The Student’s t-test at 5% probability indicates that the differences are insignificant, representing an accuracy of 97.04%. These results support the use of stereolithographic modelling of female reproductive organs in the pursuit of further aims in this research programme.

Key words: stereolithography, biomodel, spiral computed tomography

Imaging of female reproductive organs poses many difficulties. The principal reason for this is the similar densities of these organs and the surrounding tissues. The use of contrast media confers few advantages. Thus the fabrication of a biomodel, and validation of imaging procedures for its use, would facilitate the study of many abnormalities of the reproductive system. This paper demonstrates the validation of a biomodel of female reproductive organs. Datasets presented were obtained by directly scanning female reproductive organs removed from a patient during surgery. This enabled the acquisition of data without performing procedures such as image segmentation and grey scale threshold selection.

Computer visualisation techniques for rendering 3D reconstruction such as high resolution multiplanar imaging techniques like computed tomography (CT), spiral computed tomography (SCT), magnetic resonance imaging (MRI) and 3D echocardiography have been well established [1]. Computer models not only allow 3D measurements, but also facilitate diagnosis, the practicing of surgical techniques, performing of model operations and design of individual prosthesis [2,3]. However, there are occasions when 3D viewing may be inadequate and the surgeon would prefer to be able to handle a biomodel when planning a procedure. This is the case where the procedure is complex, the anatomy unusual and there is a difficulty in visualising on screen or the procedure involves the use of prostheses which have not been included in the computer simulation.

The advent of SCT and stereolithography has revolutionised thinking and investigation methods in medicine. Stereolithography (SLA) was pioneered by Charles Hull of 3D Systems in Valencia, California in 1984. It was first used for the components in the motor industry. In stereolithography, the object is fabricated...
layer by layer by the polymerisation of selected regions of a tank of UV sensitive resin. The technology is now being applied on plastic surgery, particularly in the craniofacial and maxillofacial plastic surgery domain and for neurosurgery systems [4,5,6,7]. An additional advantage is that it facilitates explanation of the procedure for patients [8]. It may also be used to obtain measurements for customised prosthetic implants, often designed by mirroring of the unaffected side [3]. A biomodel could also be scanned repeatedly by ionizing radiation without directly affecting patients.

Previous papers have described the fabrication of models of many aspects of the human body, especially of bone [8,9,10,11]. However, a biomodel of female reproductive organs has not previously been attempted. The objective of this study is to fabricate and to validate a biomodel of human female reproductive organs.

**MATERIALS AND METHOD**

**Scanning protocol**

The SCT scans were carried out on a Picker PQ 6000 scanner (Cleveland, Ohio, USA) with a $512 \times 512$ matrix size at 130kV and 150mAs. The section thickness was 1mm and the table speed was 1mm/sec, resulting in a pitch of 1. The axial images were reconstructed with a high-resolution algorithm in steps of 0.5 mm. The field of view was 240 mm resulting in a voxel size of $0.468 \times 0.468 \times 1$ mm. A total of 217 continuous axial scans were acquired. The scanning protocol of SCT is shown in Table 1.

The 3D software programme ANALYZE (V5.2 Biotechnology Computer Resource, Mayo Foundation, Rochester, USA) was used for image analysis and 3D image reconstruction. The programme provides an environment for the interactive visualisation and manipulation of 2D, 3D and 4D biomedical images. An integrated set of tools is provided to allow data to be interrogated in both two and three dimensions. Three dimensional rendering tools are integrated with two dimensional orthogonal displays to allow real time reconstruction of conventional 2D images. It was used here to see the different aspects of the 3D image of the female reproductive organs (Fig. 1).

**Contrast medium introduction**

Female reproductive organs were placed on a thick gauze that could absorb any excess water, and a contrast medium was injected into the uterus. It was important that the Fallopian tubes were extended in order to resemble their normal posture. This ensures that the tubes do not twist together at the end. The outer end of both tubes (fimbria) was then sealed with threads tied neatly in secure knots. The cervix was slightly elevated with gauze to ensure that the contrast medium remained in the uterus. Both of these measures helped to keep the contrast medium inside the organs. 30cc of 1% water-soluble telebrix 35 (a sodium and meglumine ioxithalamate 35% solution; also known as Telebrix 35, Guerbet, Aulnay/s/Bois, France) was injected into the organs with a syringe. After pulling out of syringe, the cervix was sealed with gauze as soon as possible.

**Model production**

All the rapid prototyping techniques rely on a software interface that takes computer-aided design (CAD) information, and converts it to a .STL type file format. This format is derived from the name STereoLithography, this format is currently the accept-

![Table 1. SCT scanning protocol for female reproductive organs on Picker 6000](image)

<table>
<thead>
<tr>
<th>Scan time</th>
<th>1.0</th>
<th>Index</th>
<th>0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>mAs</td>
<td>150</td>
<td>Kv</td>
<td>130</td>
</tr>
<tr>
<td>Pitch</td>
<td>1</td>
<td>Algorithm</td>
<td>sharp</td>
</tr>
<tr>
<td>Focal spot</td>
<td>small</td>
<td>Image size</td>
<td>240mm</td>
</tr>
</tbody>
</table>

**Figure 1.** 3D reconstruction by ANALYZE V5.2. a. Front view, b. Bottom-oblique view
ed industry standard. The .STL format of female reproductive organs data was transferred to a stereolithography 5140 (500/40)-stereolithographic machine (3D SYSTEMS Inc., Valencia, USA) to produce the biomodel. A computer-directed laser beam draws the digital CT scan information onto a platform in a basin of synthetic liquid resin. Wherever the ultraviolet laser light intersects the liquid resin, the resin solidifies due to polymerisation. Once one layer is drawn, the platform is lowered slightly beneath the liquid resin surface. This is followed by the next interpolation of the CT scan that is drawn by the computer on the top of the previous layer. The process conditions used were: Helium-Cadmium laser power 890 mW; beam diameter at fluid surface 0.30 mm, scanning speed 431.8mm/s, hatching space 0.15m, layer thickness 0.15 mm. When the first layer is built (X-Y plane), the platform lowers slightly in the vat (Z-axis), and a new layer is polymerised over the first one (layer thickness: 0.15mm; material: Epoxy Resin). Once the biomodel is built completely, it is then moved to an UV oven for post-curing. The time required for production of the replica was approximately 6 hours. There a useful website provides SLA fabrication process for readers who may be particularly interested in this subject [12].

### Dimensional analysis

In order to analyse the accuracy between the original organs and the stereolithographic model, the authors used statistical methods to analyse the differences between them. The workstation was used with the Picker PQ 6000 system to generate a 3D image of the biomodel. Three different observers took fourteen measurements for the purposes of objectivity and accuracy. These measurements are as follows:

1. the length of the left Fallopian tube;
2. the length of the right Fallopian tube;
3. the width of the proximal cervix;
4. the width of the middle cervix;
5. the width of the distal cervix;
6. the length of the right side fundus to cervix;
7. the length of the left side fundus to cervix;
8. the length of the anteroposterior fundus to cervix;
9. the inner diameter of the proximal left Fallopian tube;
10. the inner diameter of the middle left Fallopian tube;
11. the inner diameter of the distal left Fallopian tube;
12. the inner diameter of the proximal right Fallopian tube;
13. the inner diameter of the middle right Fallopian tube;
14. the inner diameter of the distal right Fallopian tube.

The unit of all measurements was in millimeters (mm). Measurements of (6) to (8) were taken from the top of the uterus to the bottom of the cervix along the curved surface of the biomodel.

### Statistics

The absolute difference is derived from the original value minus the biomodel of the correspondent measurement. The rest of them were calculated by the same method. The relative difference of each was calculated and expressed as a percentage. It was deduced by the smaller value of each measurement divided by the larger one of the correspondent measurements and then multiplied by 100[13]. All values were expressed as both mean ± standard deviation (SD) and standard error of mean (SEM). Correlations of measurements obtained from original and replica were both assessed by Student's paired-sample t-test and by linear regression analysis. The Student's paired-sample t-test is used to test the null hypothesis that the mean of the population from which the data sample is drawn is equal to a hypothesised value. The hypotheses are:

$H_0: \mu_1 = \mu_2$ (Null hypothesis: means of two groups are equal)

$H_1: \mu_1 \neq \mu_2$ (Alternative hypothesis: means of two groups are not equal)

The null hypothesis in our study is that the average measurements between biomodel and real organ are equal. If $p$ value is less than 0.05 ($p<0.05$), the authors reject this null hypothesis which implies that the two samples are different, whereas the $p$ value is greater than 0.05 ($p>0.05$) reflects that they are virtually identical.

The linear regression is a statistical technique used here to estimate the relationship between original and biomodel. The correlation coefficient, $r$, measures the strength of the association between variables. The most interesting parameter in a linear model is usually the slope. If the slope is zero and the line is flat, so there is no relationship between the variables. Inversely, if the slope is one and the slope forms a diagonal line, that it reveals a perfect correlation between two samples, say original and biomodel. In this paper, all datasets were carried out with the aid of SPSS/PC version 10.0.

### Results

The overall appearance and structure of this model is a yellow semitranslucent object of 160 gram with a density of approximately 300 Hounsfield Unit (HU). Careful observation showed a horizontal layered appearance corresponding to the tomographic construction of the model (Fig. 2).

At first sight, the quality of reproduction seems to
be excellent. Features such as the Fallopian tubes are clear. A more meticulous observation reveals a little surface roughness. The tiny leaks on the surface of the Fallopian tubes were noted when the authors injected water with a syringe into the cervix to ensure that the passages to both Fallopian tubes were clear. The authors patched the small leaks with the same material as that of the biomodel (i.e., epoxies resin), and an appropriate type of glues (α-cyanoacrylate adhesive).

The Figure 3 shows the appearance comparison between the original female reproductive organs and the stereolithographic model.

Results of the dimensional measurements undertaken are summarised in Tables 2 to 5 and Figure 4, which show statistical outcomes between the measurements of the original female reproductive organs and the stereolithographic biomodel. Table 2 shows the listing of variations between original and biomodel by three observers. It reveals the largest measurement is No. 8 of the biomodel, whereas the smallest measurement is No. 10 of original organ. The No. 11 measurement of original organ was quantified identically by all three observers, whilst the greater spread occurred in measurement No. 8 of the original organ with a SD value of ±5.54.

Table 3 shows the comparison of average dimensions and the analysis of dimensional variations. This Table indicates that the differences between the various measurements are either positive or negative, which reflects that the biomodel can be over or under-dimensional by observers. The greatest difference between original and biomodel is in No. 8 with the value of 9.53, while the smallest change is in No. 9 with the value of 0.05. Statistically, the absolute values of difference range from -9.53 mm (minimum) to 0.7 mm (maximum), corresponding to relative differences of 96.64% and 97.53%, respectively. Expressed as a percentage, the mean dimensional accuracy is 97.04%. In general, from the absolute dif-

![Figure 2. A close-up picture demonstrating the layered surface texture of the biomodel](image)

Figure 3. Comparison between original organs and stereolithographic biomodel by their appearance. a. Original b. Biomodel.

<table>
<thead>
<tr>
<th>Measurements</th>
<th>Original (mm)</th>
<th>Biomodel (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± Std D</td>
<td>Std Error of mean</td>
</tr>
<tr>
<td>No 1.</td>
<td>146.16 ± 2.02</td>
<td>1.16</td>
</tr>
<tr>
<td>No 2.</td>
<td>169.99 ± 1.85</td>
<td>1.07</td>
</tr>
<tr>
<td>No 3.</td>
<td>35.21 ± 0.45</td>
<td>0.26</td>
</tr>
<tr>
<td>No 4.</td>
<td>26.45 ± 1.14</td>
<td>0.66</td>
</tr>
<tr>
<td>No 5.</td>
<td>43.02 ± 1.01</td>
<td>0.58</td>
</tr>
<tr>
<td>No 6.</td>
<td>274.29 ± 3.53</td>
<td>2.04</td>
</tr>
<tr>
<td>No 7.</td>
<td>275.30 ± 1.90</td>
<td>1.09</td>
</tr>
<tr>
<td>No 8.</td>
<td>274.16 ± 5.54</td>
<td>3.20</td>
</tr>
<tr>
<td>No 9.</td>
<td>1.93 ± 7.77 × 10³</td>
<td>3.33 × 10⁻³</td>
</tr>
<tr>
<td>No 10.</td>
<td>1.92 ± 7.77 × 10³</td>
<td>3.33 × 10⁻³</td>
</tr>
<tr>
<td>No 11.</td>
<td>3.52 ± 0</td>
<td>0</td>
</tr>
<tr>
<td>No 12.</td>
<td>1.99 ± 7.77 × 10³</td>
<td>3.33 × 10⁻³</td>
</tr>
<tr>
<td>No 13.</td>
<td>2.82 ± 6.25 × 10⁻²</td>
<td>3.61 × 10⁻²</td>
</tr>
<tr>
<td>No 14.</td>
<td>3.65 ± 1.53 × 10⁻²</td>
<td>8.82 × 10⁻⁷</td>
</tr>
</tbody>
</table>
In Table 4, the data for original is derived from the absolute difference in Table 3. It was analysed by one-sample t-test to receive the mean value of -1.73 mm with a standard error of 0.8616 mm. Likewise, the biomodel mean difference is 1.73 mm which was converted from the original values, with a standard error of 0.86 mm. The mean positive difference is 1.955 mm with a standard error of 0.82 mm.

Table 5 was derived from comparing the trial average values of the original and the biomodel in Table 3. With paired-sample two tailed t-test, it shows $t_{13} = 2.01$ falling between the 95% confidence level of difference at the lower value of -0.1292 and the upper value of 3.5935, $t_{13,0.05} = -0.1292$ and $t_{13,0.95} = 3.5935$, with $p$ value of 0.066. In this case, $p$ value is greater than 0.05, so we fail to reject the null hypothesis. There is no significant difference between the average measurements between original organs and biomodel.

Subsequently, the authors also apply the linear regression to analysis the similarity of both samples. The outcome is shown in Figure 4 and that shows highly positive correlation when comparing average dimensional measurements between the corresponding features. The $r = 0.99$ also reveals a very close similarity between two samples.
DISCUSSION

Stereolithographic models are now used increasingly by the industry to design components for numerous applications, including automobiles, aircraft, and computers. Recently, this technique has also been applied in medicine, mostly to fabricate replicas of skeletal structures from CT scans to aid complex maxillofacial surgery and radiotherapeutic treatment planning [1]. Ultimately, true 3D representation of female reproductive organs structures may be better achieved by creating tangible models. Such models can serve as a hard copy of such data sets and can provide both visual and tactile information of female reproductive organs structures that may enhance the current display on a computer screen.

In order to determine the accuracy of the stereolithographic process, it is necessary to ensure that the stereolithographic model is compared against an object of known or measurable spatial dimensions. Potential sources of error are present in each stage of the path, from SCT scanning to stereolithographic model fabrication. The need for future enhancements in some of these subprocesses is envisaged for applications where the current level of accuracy is not sufficient.

The mean dimensional accuracy value of 97.04% shows that it is possible to obtain a stereolithographic model that is accurate to within the pixel dimensions of the original SCT images. Concerning the dimensional accuracy, Swaelens & Kruth [9] reported an average deviation of 0.25 mm for the modelling of a dry human tibia. This accurate result may be related to the absence of surrounding soft tissue and the simple anatomy of the tibia. Klimek et al [14] indicated an accuracy of between 0.2 to 0.5 mm, and Mole et al [15] obtained an overall distortion less than 3.2%. Barker et al [16] gained an average dimensional deviation of 0.85 mm; Wolf et al [10] made a stereolithographic model of a dry skull using the same procedure and obtained a 0.25 mm accuracy. Barker et al [13] reported the average difference of 0.12 mm with an accuracy of 97.9% for mandibular fabrication. Santler et al [11] compared the accuracy of biomodels fabricated using stereolithographic and milling techniques. He observed that the stereolithographic and milled biomodels showed the mean deviations of 0.81 mm and 0.54 mm, respectively. D’Urso et al [8] showed the accuracy of a skull scan to be approximately 0.8 mm. Binder et al [1] performed work with a stereolithographic model constructed from echocardiographic data. He gained highly accurate results, which showed the volume and the dimensional mean difference of 0.25 mm and 0.03 mm, respectively.

In this study, the result of dimensional analysis shows an average positive difference of 1.955 mm with an accuracy of 97.04%. It shows no statistically significant difference between the measurements on the original and the biomodel (=-0.1292 and =3.5935, p>0.05). Despite comprehensive reviews of related published work, it appears that either little or no work has been done using a CT monitor to obtain organ measurements. Previous researchers, who are cited above, measured the original organs and replicas using a set of Vernier calipers. Thanks to both the advents of SCT and its powerful workstation, a more precise and convenient means of distance measurement has been made possible. The authors measure the replica dimensions not only by using a set of calipers but also using a screen. Consequently, it is difficult to compare the accuracy between the two measurements.

The accuracy of biomodel fabrication is influenced by several factors, such as data acquisition, scan speed, and the fabricating process [2,10,18,19]. The anatomical detail displayed in biomodels is directly influenced by the quality of the original CT images [2,10]. The acquisition of three-dimensional CT image data can incorporate errors due to patient motion, beam hardening and partial volume effects [10]. Surface tilting of objects from volumetric data can also be subject to errors associated with the selection of an appropriate image threshold and the nature of the tilting algorithm itself. The effect of threshold variations upon the anatomical detail displayed in the stereolithographic model can be predicted by the creation of interactive three-dimensional displays on a computer graphics terminal, hence ensuring that a model of appropriate detail is produced by the stereolithography machine. Santler et al [2] also indicates that the scan speed (pitch) is also the limiting factor for the accuracy. Therefore, his work uses the smallest possible speed to gain each point of the object and to have as many pixels as possible.

The stereolithographic modelling technique can introduce errors due to model shrinkage during building and post-curing process. Ashley [17] states that the fabricating process is one of the causes of inaccuracy during biomodel fabrication. He indicates that there is approximately 3% volumetric shrinkage during laser induced polymerisation. The polymer contracts another 2-3% of volumetric shrinkage during the post-curing process. Sader et al [19] agrees with this statement and highlights that a reduction in the weight of the biomodel was noticed. He finds a 3% weight loss after one month and up to 5% after six months. In this study, the 160g biomodel was built in
June 2000. It was stored in a regular paper box with protective sponges to prevent any damage and was placed in a drawer to keep dry and avoid penetration of sunlight. There is one gram difference from the original with reduction of 0.625% after 5 months. It remains unchanged until December 2001, but no further investigation has been made on this issue.

With regard to the artefacts, Barker et al [16] proposes that the low CT signal produced by thin bones creates the defect known as pseudoforamen. This occurs when signal thresholding techniques are used for creating three-dimensional displays of structures. The authors also indicate that the defects can be minimised by decreasing the CT collimation thickness. Barker et al [16] also indicates that the partial volume effect on thin bone structures (less than 1 mm) explains the presence of pseudoforamina in his biomodel. He suggests that the use of a higher quality CT acquisition technique (use of a 1024 × 1024-matrix size, decreasing the section thickness) is necessary. In this study, there were tiny leaks noticed at several points on the surfaces along the Fallopian tube regions of the biomodel. The authors fixed these leaks with thin resin fragments and appropriate glue, which were provided by the biomodel manufacturer.

There are several limitations of the stereolithographically modelling. Actual production of the stereolithographic model takes between 12 and 24 hours on the stereolithography machine, depending on the machine version [4], memory capacity of the stereolithography control computer [20] and depending on the structure being replicated [21]. The biomodel for this project was built for 6 hours, it was not so time consuming when comparing with the works by previous researchers. This is because the authors use the advanced SLA machine and the replica is not a big and complicated issue. However, the SLA model is not somewhat suitable for the urgent need in the casualty department.

Additional time is required for the computer data processing and transferring. The entire stereolithography biomodelling process currently takes up to 1-2 weeks to complete [21]. However, further streamlining of the process is in progress and will reduce the total production time to 2-3 days after gaining further experience. In this study, using the computer, it was endeavoured to produce the hollow pathway of the female reproductive organs as it occurs in nature. It depends on the complete filling of the cervix, uterus and Fallopian tubes by injection of contrast media and the complete sealing before SCT scanning. The computer, with the aid of Boolean operation, allows manipulation of the model and helps to determine the appropriate time to remove the contrast media from the model on the screen per se. Yau et al [4] also spent a lot of effort to improve the accuracy of fabrication of a biomodel for the 3D object segmentation. Binder et al [1] depicted that partial volume effects is caused by the segmentation, which determines whether a pixel of the image corresponds to tissue or background.

Another potentially limiting factor is the fabrication cost. Dolz et al [21] spent US$ 2,000-3,000 per case in the development of facial models to reconstruct the face of soldiers who were shot in the battle. Grolman et al [22] spent US$ 1,000 building a tracheostoma, McGurk et al [23] spent around £ 2,000 fabricating a facial skeleton. D’Urso et al [24] also reveals that the cost issue is the limiting factor for the stereolithography. He spent US$ 570 on a fetal face model with stereolithography. In this study, excluding the expenditure on the preparation and computer manipulation tasks, for the 160 g life-sized model, it costs approximately £ 500. The price could be undoubtedly reduced with more widespread commercial applications in the future.

In conclusion, the removed organs were scanned directly and easily. This has the potential to reduce the time for preparation and image manipulation. However, the organs could not be removed for every test for the human body and the manufacturing time of 12-24 hours must be considered in the future procedures. Despite these drawbacks, the work still proposed the feasibility of developing the method on the female reproductive system fabrication. It is also planned to use this biomodel to deploy virtual reality scheme in the future to see if SCT can detect the minimum size lesion in the female reproductive organs. The authors are endeavouring to share their experiences with all the readers who are interested in this project.

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子宮輸卵管立體光照模型的製作及其精確性研究

林政勳¹²  Catherine O’Neill²  Martin O’Donnell³

中台醫護技術學院 放射技術系¹
英國 Ulster大學生物醫學研究所 放射醫學組²  電機與材料科學研究所³

本研究在評估以螺旋電腦斷層攝影掃描從病人身上摘除之女性生殖器官，包括子宮、輸卵管
與卵巢，經立體光照模型所製作出的生物模型之精確性。為求量測客觀性，我們選定三名不同
的測量者在 CT 螢幕上測量經過選定的生物模型與原來器官共 14 點並記錄。其結果得知生物模
型比原來的器官略大，平均差異為 1.73 mm，標準誤為 0.86 mm，平均絕對值差異為 1.955
mm，其標準誤為 0.82 mm。t 值檢測在百分之五的信心水準下為不顯著，顯示模型與原來器官
十分相似，精確度為 97.04%。

關鍵詞：立體光照模型，生物模型，螺旋電腦斷層攝影