

**Female Calvaria Shape Digitization:
A Method to Create a Database of Scalp Shapes
to be Used in Equipment Design**

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Solutions Through Innovative Technologies, Inc.

Final Report

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EXECUTIVE OVERVIEW

At the request of our customer Mr. Mark Richter of the United States Marine Corp/Marine Expeditionary Rifle Squad (USMC/MERS), the United States Air Force (USAF) Anthropometry Laboratory (711 HPW/HP/HPIF) developed a head fixation rig and a method to collect point data, through hair, that could be used to represent the geometry of a scalp. This work was driven by the inadequacy of current head scan data and the confounding effects of hair volume. An improved representation of head geometry, particularly in the form of a large database, will become a much needed resource to improve helmet design.

This report details the methodology developed that will be used to conduct scalp shape surveys in order to create a functional database. This methodology includes descriptions of a head fixation rig, the data collection method, and of software that automates the integration of the data collected with the USAF rig and method. This software, developed by the Morphometrics Laboratory at Florida State University (FSU) uses the collected scalp point data to generate a smooth, polygonal mesh head form in proper relation to a 3D scan of each subject's face (Figure 1). The resulting head database will be able to serve as a helmet and helmet mounted equipment (HMDs) design resource.

A detailed description of the study background is given in Section 1, followed by descriptions of the hardware and data collection procedure developed. The methods for assessing current accuracy and repeatability measures are reported in Appendix I. Appendices II and III of this report are intended as a manual to accompany on-site training for using the rig to collect and process data.

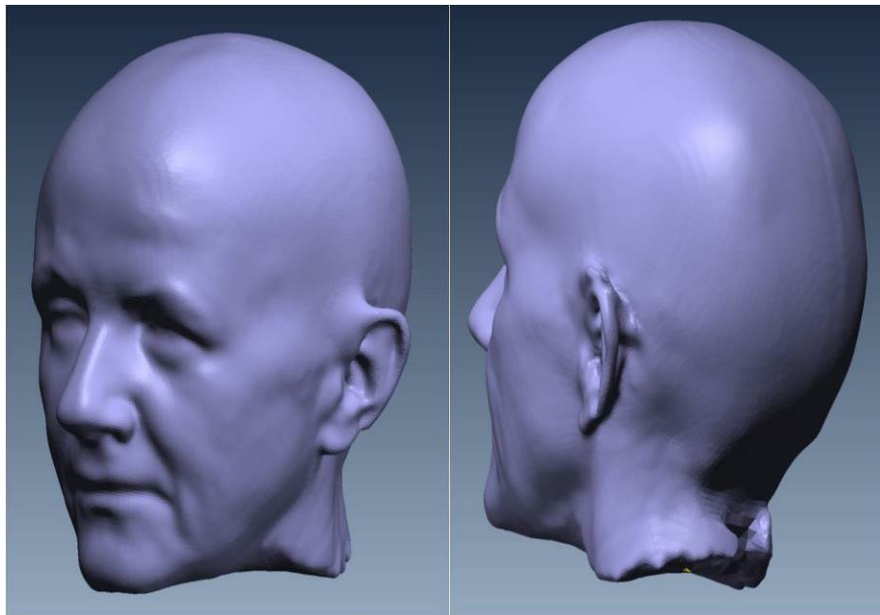


Figure 1. Example final product: face scan aligned with thin plate spline mesh of digitized scalp. Some hole filling and smoothing was done

1.0 BACKGROUND

The Anthropometry Lab of the USAF 711th Human Performance Wing undertook a study in 2010/2011 to attempt “virtual fit-testing” of helmet design concepts (Zehner et al 2011). This study attempted to align 3-D scan data of human heads within CAD models of the inside of a prototype helmet (Figures 2 – 4). Measurements were then made to determine (among other things) the offset of the helmet from the head in order to determine helmet liner thickness and shape.

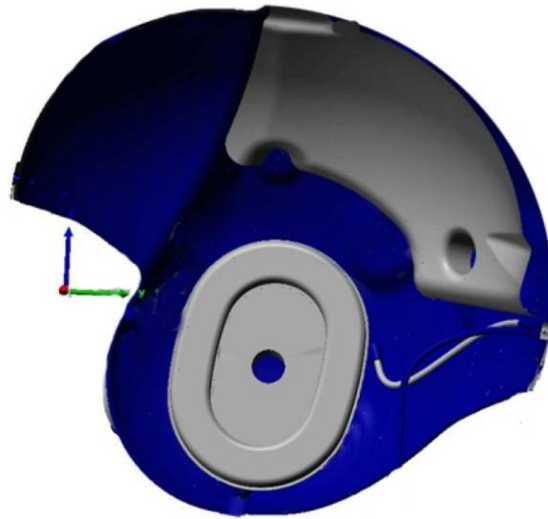


Figure 2. Inside Surface of a Prototype Helmet from CAD

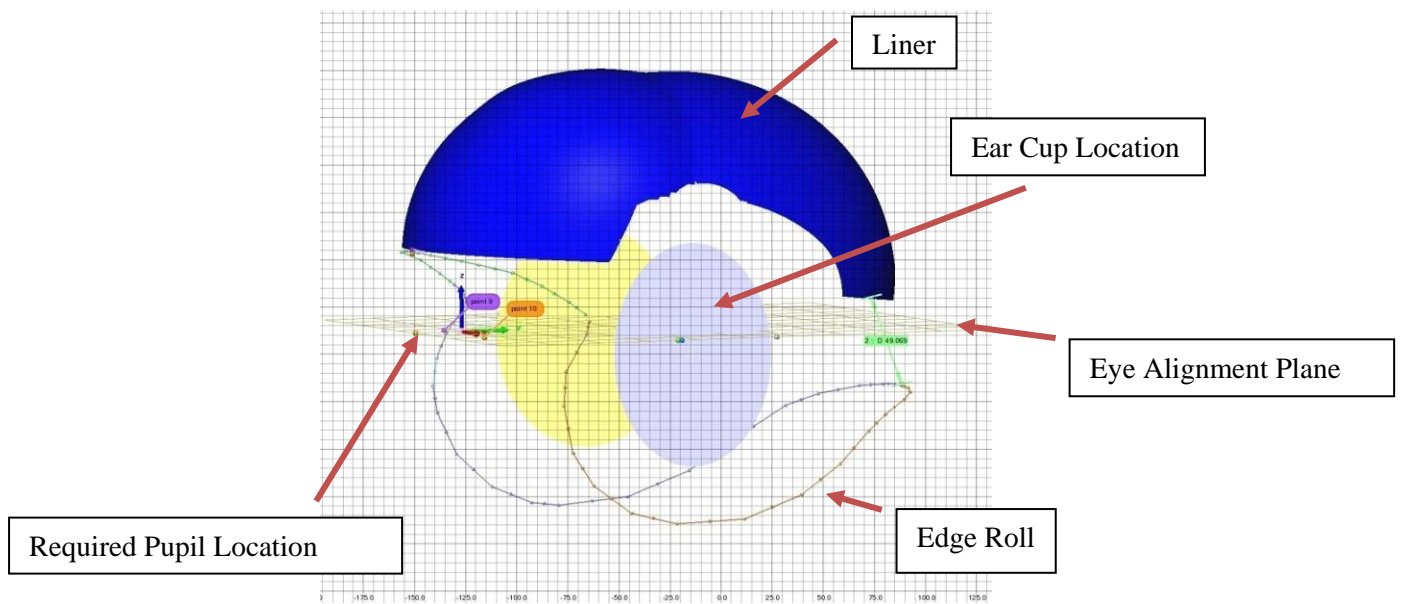


Figure 3. Relevant parts of Helmet for Virtual Fitting

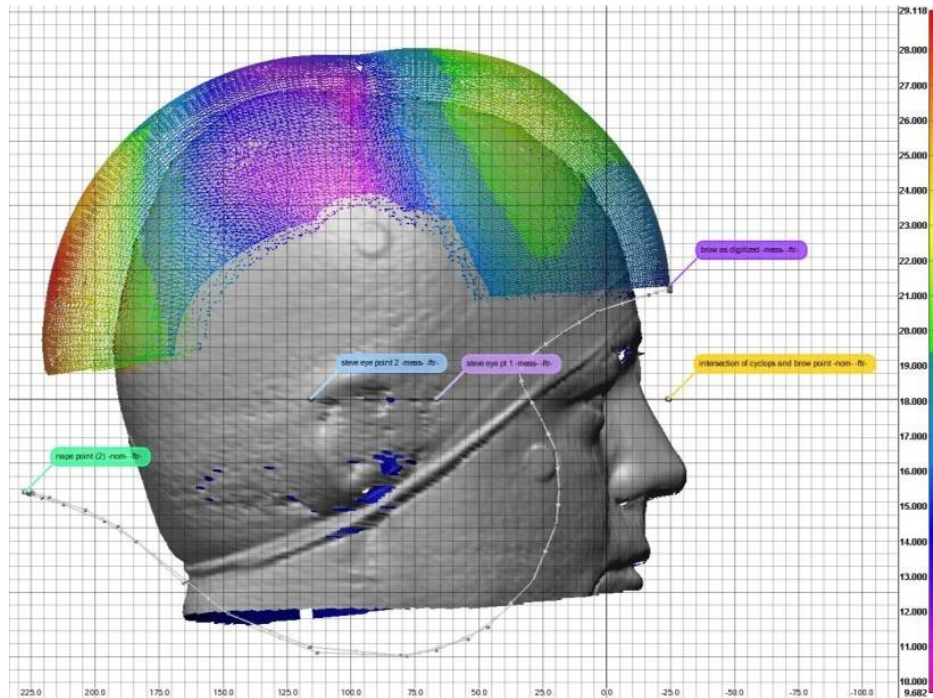


Figure 4. Color Map of Helmet Liner Offset (mm)

It became immediately obvious that the shape of the head scans were distorted due to the “bald cap” worn to flatten out the hair mass and the hair that was underneath the cap. This shape problem was exaggerated in many female head scans due to hair length and volume. Notice the shape at the back of the neck in Figure 5. The distances shown in the figure represent the difference between the apparent surface of the head and the scalp digitized through the hair (to be discussed below). Scans of males with shaved heads worked quite well, but there were not many of them in the database.

Another problem with this approach is that measurements taken from scans have no tissue or material compression. They are essentially solid objects. Caliper measurements on the other hand, go through the hair and also slightly compress the tissue of the scalp. This disparity in method becomes a problem when accommodation requirements are based on caliper measurements and the design or “virtual fit-test” uses scan measurements for verification. To examine the effect of this issue, measurements of head length and head breadth taken over the bald cap, in the scan, were compared to the same traditional measurements taken with calipers on the same individuals. The results are shown in Figure 6. The two distributions (represented by the ellipses) are strikingly different.

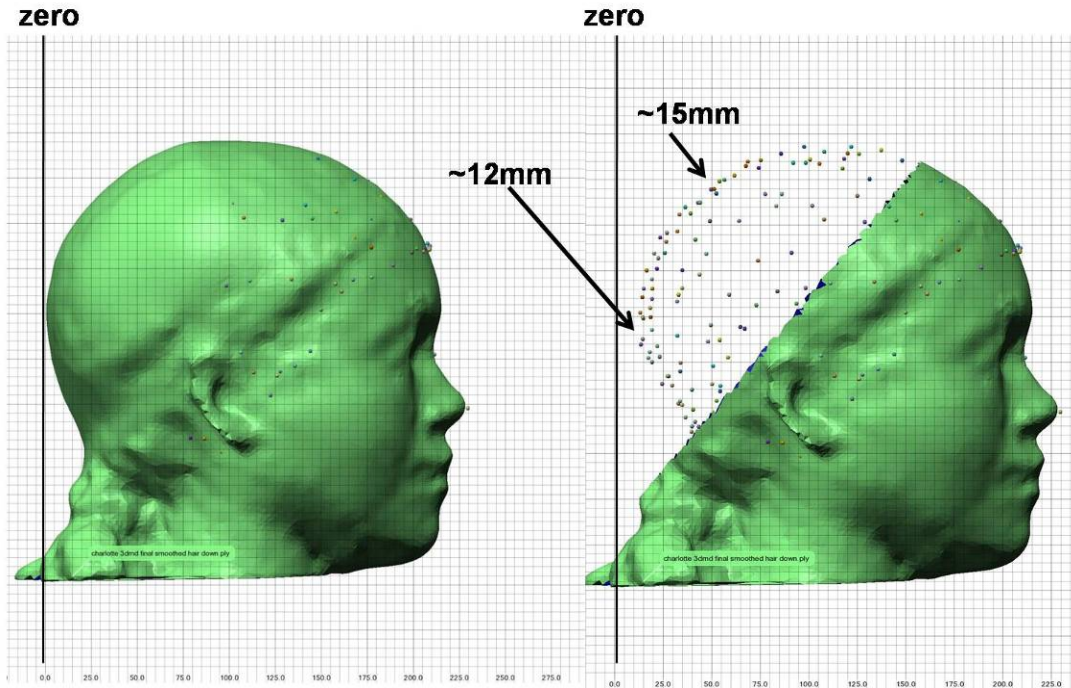


Figure 5. Differences between scan bald cap and digitized scalp

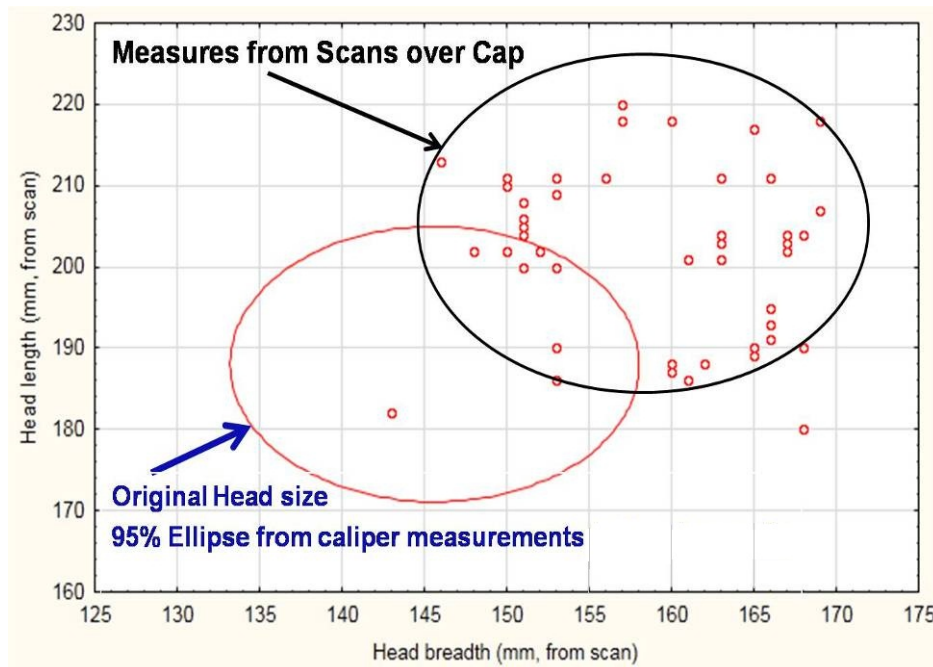


Figure 6. Comparisons of caliper measurements with scan measurements

The conclusion from this study was that current scan data are unusable for virtual fit-testing and that a method for digitizing the shape of the head *through the hair* is needed for this work to continue.

In 2013 the USMC/MERS funded a study to develop this method. This report documents the method developed for digitizing the shape of the scalp for head mounted equipment design. In very general terms the approach is as follows:

- Head Stabilization: develop a rig to limit head movement (Figure 7).
- FARO Probed 3-D Points: probe through four to five hair parts on each side of the mid-sagittal plane for a total of ~200 data points (Figure 8).
- Align Probed Points With Scan: four landmarks and skin overlapping boundary lines for alignment of a face scan to probed points (Figure 9).
- Surfacing Probed Points: software using Thin Plate Splines (TPS) will be used to surface the probed points (Figure 10).



Figure 7. Head Stabilizing Rig



Figure 8. Hair Parting Scheme

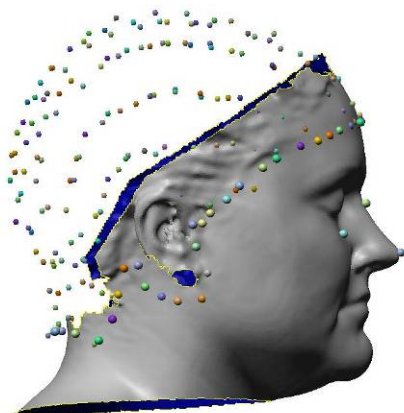


Figure 9. Digitized Scalp and Landmarks aligned with face scan

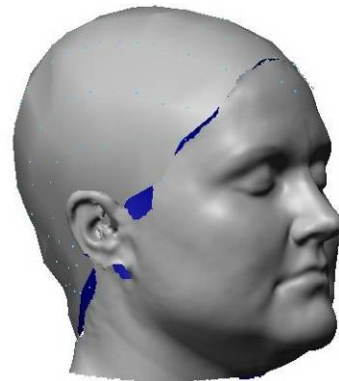


Figure 10. An example of the generated scalp shape

2.0 DESCRIPTION OF HARDWARE

The head fixation rig is essentially a highly modified ophthalmological head rest (Figure 11). Elements, such as the neck strap, temple stabilizers, and chin rest were added to decrease subject movement. These elements are all adjustable and should accommodate male and/or female subjects of varying head size. The chin rest must be adjustable up/down and must tilt fore/aft. It is utilized in a seated position with a chair providing additional up and down adjustment.

During its development phase the head fixation rig went through several iterations resulting in measurable and improved accuracy. Current accuracy test trials, comparing digitized scalp points with associated scalp scans of hairless men, offer a maximum error range of +/-4mm, above and below the actual scalp scan, and a maximum standard deviation of 1.7mm.

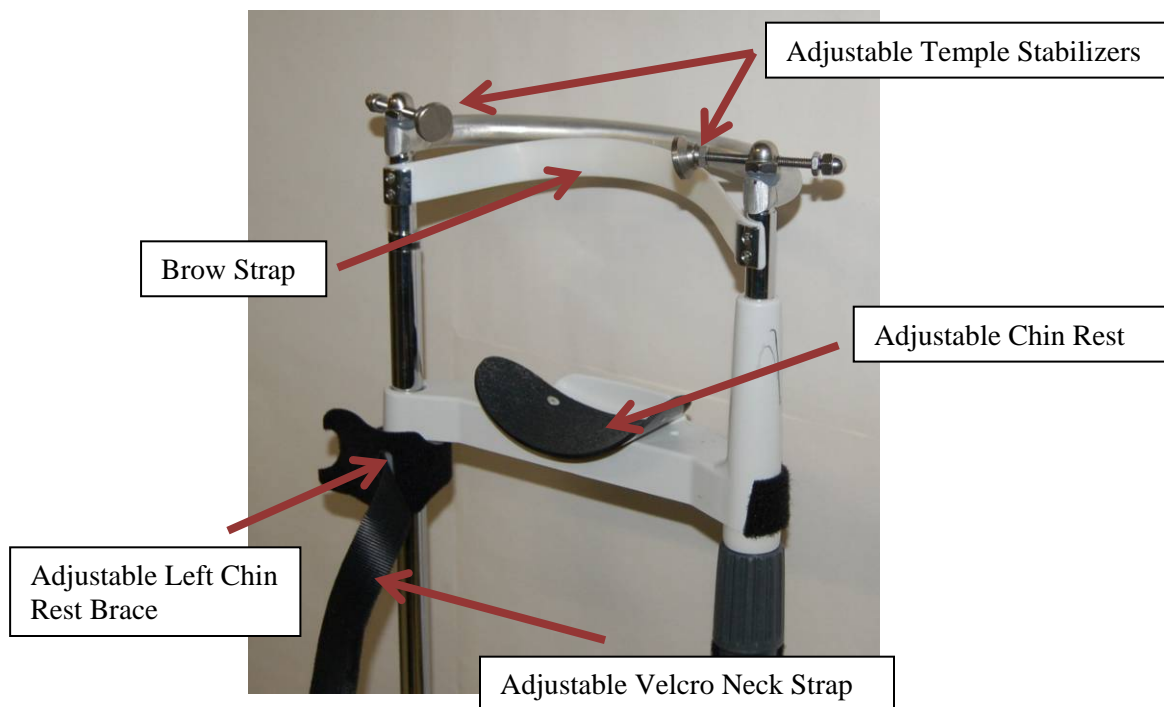


Figure 11. Details of Chin Rig

The head fixation rig is mounted on the top of an aluminum slab (Figure 12) to which the coordinate measuring machine, a FARO arm, is also attached. Accurate measurements require a stable surface – i.e. a sturdy table or workbench on which the aluminum plate of the head fixation rig can be clamped. Just as the head fixation rig is attached to the plate, so too is the FARO arm. In this way all data collected are in a static coordinate system.

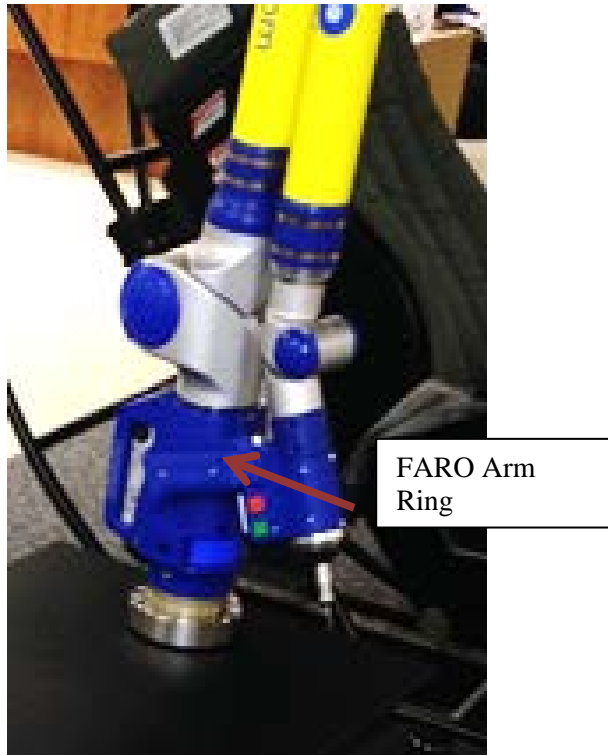


Figure 12. FARO Arm location on the Aluminum Plate

3.0 PROCEDURE

By digitizing through hair and aligning the data to its facial scan, this method can be used to represent any scalp. The entire data collection process should take less than one hour. A detailed procedure manual, with checklist, is provided in Appendix II.

3.0 Data Collection Equipment Utilized

For method development the USAF used the FARO arm in conjunction with Innovmetric Polyworks software to collect XYZ coordinate point data. The Artec Eva Scanner (as shown in Figure 13) was used to collect initial head scans of subjects. Other 3D scanners are available and could be used as long as the generated scalp shape is validated against a previously tested combination of hardware and software on a baseline head form. Collection procedures for the FARO arm data should be followed as closely as possible.

The standard 6mm Hard Ball Probe (Figure 14) was selected due to collector preference and its usefulness in situations where parting hair may not be possible due to hair type and length. Because the collection of XYZ coordinate points is done manually (by pressing the green button on the FARO arm grip), the data collector needs to be mindful of taking a point while making very light contact with the subject's scalp. Hence, care needs to be taken to avoid 1) taking a point with the probe tip not being in contact with the subject and, 2) pressing the probe tip into the subject, causing soft tissue deformation, subject discomfort, and possible head movement.



Figure 13. Artec Eva scanner



Figure 14. 6mm Ball Hard Probe

3.2 Subject Preparation

Accuracy increases when the data collector can see the scalp, therefore, hair parting has been implemented when a subject's hair is more than a few inches in length. This process works well for a variety of hair types, including hair that is thick, curly, and/or difficult to run a brush through easily. The parting method that has proved useful involves twisting sections of hair back in a style similar to thick cornrows (Figure 15). Hair parting instructions can be found in Appendix II.



Figure 15. Examples of hair parting scheme when scalp is visible

For hair that is too short to part, a free form procedure can be used as long as the FARO probe can glide through the hair, without catching. Both methods require the same number of “part lines” and data points collected on the scalp. However, when using the “free-form” method if the data collector can't see the scalp, the placement of points and part lines may be less accurate.

It may be useful to place an easily removable marking using a makeup pencil, as a reference guide for each part line.

All modes of data collections (FARO point probing, as well as face surface scanning) should include four reference landmarks. These can be made using a basic makeup pencil, which will wipe off easily after data collection. Originally, we included additional landmark points (for a total of eight) two at infraorbitale and two at mastoidale. These are now omitted because they did not improve the quality of the final scalp and face alignment. The four most useful landmarks are listed below and shown in Figures 16-18:

1. Two Tragions (Right and Left) – The superior point on the juncture of the cartilaginous flap of the ear with the head
2. Pronasale – The point of the anterior projection of the tip of the nose
3. Sellion – The point of the deepest depression of the nasal bones at the top of the nose



Figure 16. Tragon reference landmark placement

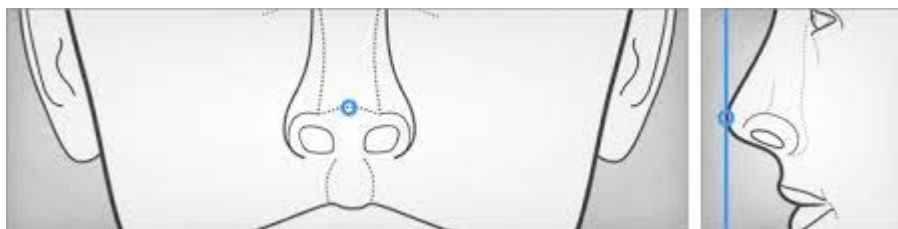


Figure 17. Pronasale reference landmark placement

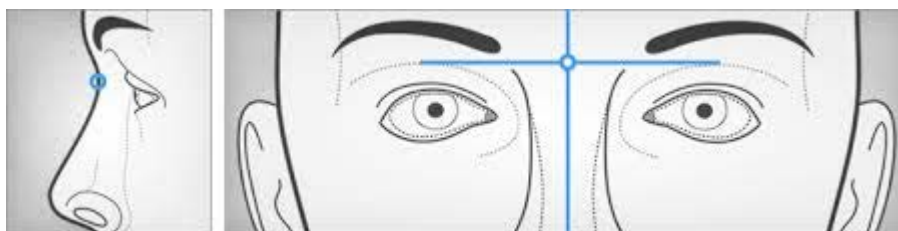


Figure 18. Sellion reference landmark placement

Photos taken from FaceBase.org: Comprehensive data and resources for craniofacial researchers.

Collections should include a brief demographic questionnaire (to record age and race/ethnicity) and these four traditional anthropometric measurements (shown in Figures 19-22):

1. Head Circumference – The maximum circumference of the head above the glabella and crossing the rearmost point of the skull. As measured with steel tape.
2. Head Length – The distance from the glabella landmark between the brow ridges to the rearmost point of the skull. As measured with calipers.

3. Head Breadth – The maximum horizontal breadth of the head above the ears. As measured with calipers.
4. Tragon to Top of the Head (TTOH) – The vertical distance between the right tragon landmark and the horizontal plane tangent to the top of the head. As measured with an anthropometer.



Figure 19. Measuring head circumference



Figure 20. Measuring head length



Figure 21. Measuring head breadth

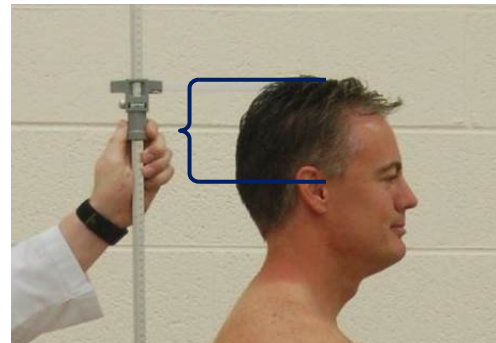


Figure 22. Measuring tragon to top of the head (TTOH)

To reduce movement and soft tissue folds at the base of the scalp, the subject should lean forward from their normal sitting position. The chair and chin rest should be at an appropriate height for them to be able to do so (Figure 23). Use of the temple stabilizers is meant to hold the subject steady, minimize movement, and make them aware if they are moving. They should fit snugly but are not intended to be so tight against the scalp that they cause discomfort and excess tissue deformation.

Preventing movement is a top priority and it is the responsibility of both the subject and the data collector. Do not use the chin rig as a hand rest during data collection. However, some light contact may be useful in steadying the hand holding the probe. Avoid bumping into the subject or their seat. Also use care when restoring the FARO Arm to resting position. Letting it hang/swing back into place can shake the setup and/or damage the probe tip.

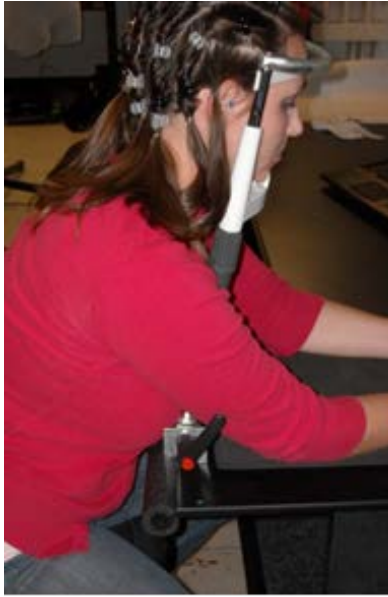


Figure 23. Example of Subject Posture

3.3 Data Collection

The four reference landmarks should be taken first, followed by a hairline or boundary line (see below, Figure 24) and scalp points. The hairline/boundary represents the border around the hair covered scalp. This boundary line is approximated with bald subjects. The FSU Morpheus program uses the XYZ coordinate (scalp) points to generate a scalp shape within this border. The landmarks are used to align the facial 3D scan with the generated scalp shape.

A second set of reference points are taken before data collection is finalized, comparing possible 3D “movement.” If comparisons between the two sets of reference points show that movement has occurred (i.e. any one landmark is $>5\text{mm}$ in 3D distance from the original), the collection process should be repeated, and brought within an acceptable range.

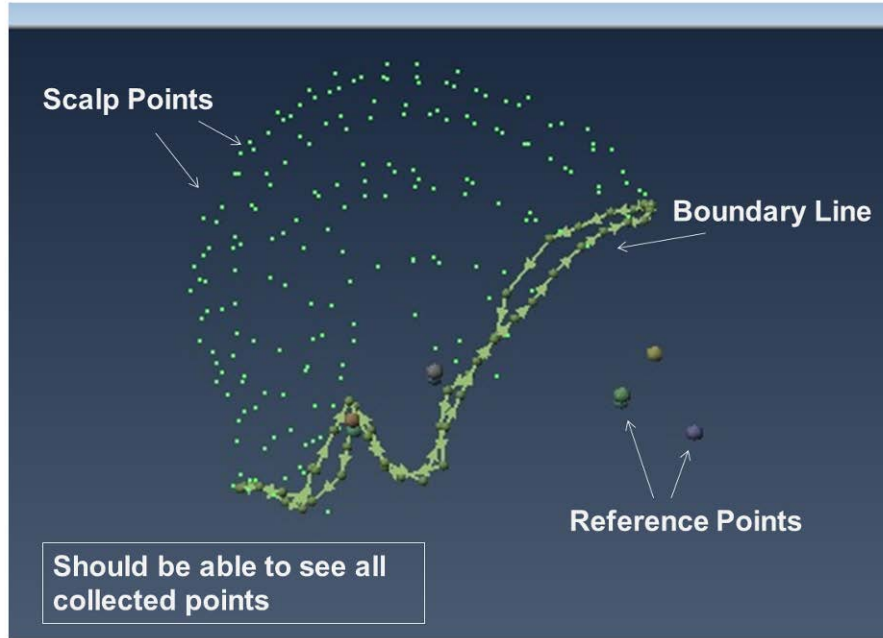


Figure 24. Screen display of collected data

The initial landmark points, the boundary “hairline points, and the scalp points need to be exported from Polyworks separately. Landmark points are also picked in the 3D face scan and are easily exported. FSU’s Morpheus software automates the process of importing and aligning the 3D head/face/landmark scan data and the FARO digitized data using the four landmarks.

A guideline for data processing is provided in Appendix III. This description is specific to the Polyworks and Artec Studio 9 software that the USAF has been using during this development phase.

The USAF used the Artec Eva scanner (as seen in Figure 13) for acquiring 3D head/face/landmark scans of subjects. Our steps for using the Artec Eva scanner are listed in Appendix II as a matter of record. It is understood that other survey teams will choose their own 3D scanners based on availability and/or preference.

4.0 CONCLUSIONS AND RECOMENDATIONS

The current USAF method for capturing scalp shape data, through the hair, uses the modified head fixation rig and the Advantage FARO arm equipped with a 6mm hard ball probe. These data are aligned to an Artec Eva 3D face scan using FSU's Morpheus software. Methods of FARO data collection and synthesis with the scan should always be the same for each survey team. However, it is likely that different teams will use different scanning systems to capture subject geometry of the head and face. Because the accuracy tests reported here are specific to our Artec scanner hardware, it is recommended that similar accuracy tests be conducted with the different scanner systems using a baseline head form.

It is clear, however, that given the ~15mm larger offsets of traditional head scans (with "bald caps" over hair), compared to the +/-4mm error (maximum SD of 1.7mm) obtained with the current collection method, scalp representation is improved with this FARO arm method. Minimizing subject movement is the key to a good scalp shape and its alignment with the face scan. The final rig additions of the neck strap and adjustable temple posts reduced subject mobility and reduced error by half.

In summary, the accuracy offered by the final system will be a function of the error introduced by the: 1) head scanning system, 2) digitizing hardware (FARO arm and Probe), 3) researcher during data collection, 4) movement of the subject while in the rig, 5) integration of the scan and generated scalp data into alignment based on reference landmarks, and 6) the final "head + scalp" mesh construction, hole filling, and smoothing. The first three of these should be random error and distribute around the actual subject geometry. The fourth is the greatest potential contributor to error and all care must be taken by the researcher to ensure the subject stays relaxed and still. The fifth type of introduced error is reduced through the use of landmark best-fit algorithms and mathematical/statistical methods. Finally, hole filling and smoothing should be done with restraint, to ensure mesh is not simplified at the expense of actual scalp geometry.

The method described here has the ability to accurately represent a scalp shape and is intended to be used to gather a database of head shapes that is representative of the size and shape variations seen in the military population. The effect of gender and race on head morphology must be considered in developing the database to assure adequate sampling. This database would be a very useful design tool for head mounted system development.

REFERENCE

Gregory Zehner, Teresa Metzger, Michael Selby (2011). *Creation of a 3-D Scan database for Helmet Design*. In Proceedings of 49th SAFE Symposium, Oct. 24-26, 2011, Reno, Nevada.

ACROYMS

United States Marine Corp/Marine Expeditionary Rifle Squad (USMC/MERS)

United States Air Force (USAF)

Florida State University (FSU)

Helmet Mounted Equipment (HMD)

Thin Plate Splines (TPS)

Tragion to Top of the Head (TTOH)

APPENDIX I: METHOD VALIDATION AND ACCURACY TESTS

Below, validation for the USAF data collection method is presented. These validation tasks occurred prior to the start of the actual survey (June 2015). The following validation issues are addressed: a) number of hair parts, and points per hair part, b) landmark choice for alignment of FARO point data to scan, and c) accuracy and repeatability.

1. Number of Hair Parts, and Points per Hair Part

Since our goal was to define a protocol that was the most efficient (using the minimum number of parts and points) without sacrificing accuracy in scalp representation, we needed to determine the minimum number of points needed to adequately represent a subject scalp shape. To do this, a subject with no hair was scanned. Lines of points (representing hair parts), on the scalp, were defined in Polyworks (not with a FARO arm) to represent the digitizing of a female subject's scalp through hair. Below, in Figure 1.1, approximately 500 points on 22 parts were selected on this scan to represent his scalp geometry. A NURBS surface was created using the 500 points and compared to the original scan. Surfaces were also created using a subsampling of 300 points/14 parts and 150 points/7 parts (Figure 1.2).

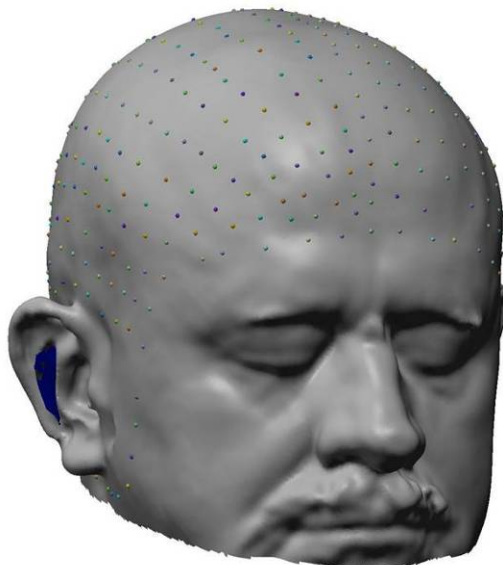


Figure 1.1: Scan of hairless subject used to generate ~500 anchored scalp points

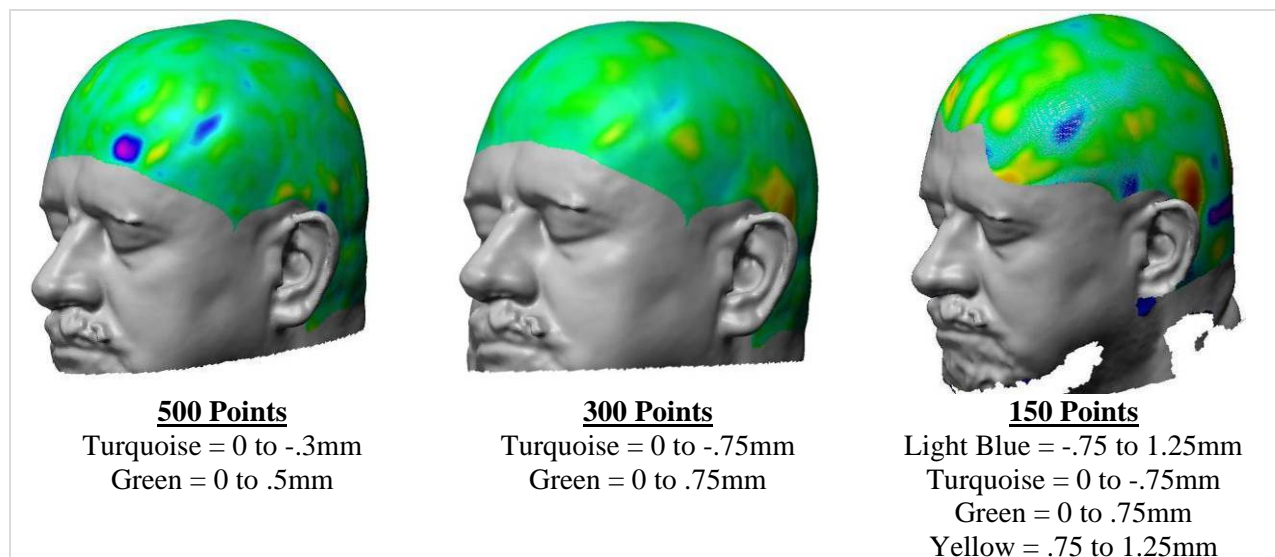


Figure 1.2: Color Map differences between NURBS surfaces created from specified scalp points

In Figure 1.2, the color maps show the results of the comparisons of the NURBS surfaces to the original scan from which the points were sampled. The surface generated from the 500 points (and 22 parts, left image) represents an approach in which too much time and difficulty would be imposed to collect so many points and parts. Its mosaic of turquoise and green represent a deviation from the original scan of $-.3\text{mm}$ to $+.5\text{mm}$. This range of deviation serves as a base line. For instance, the 300 point (14 part, center image) turquoise and green represent slightly larger deviations of $-.75\text{mm}$ to $+.75\text{mm}$. Finally, the 150 point (7 part, right image) deviates from the original scan ranging from -1.25mm to $+1.25\text{mm}$ (represented by blue, turquoise, green, and yellow). Based on these results, and experience practicing with varying part numbers, we selected to target ~ 200 points using 9 parts. This amount of data takes about 10 minutes to collect and should not contribute more than $\pm 1\text{mm}$ to the total error in the method.

2. Anatomical Landmark Choice for Alignment of FARO Data and Head Scan

Anatomical landmarks (makeup pencil marks) are placed on the subject in order to produce a set of 3D coordinates that are shared by both the scan and the FARO digitized data. These landmarks serve as the first step for registering or aligning the two types of data and include: 1) Right Tragian, 2) Pronasale, 3) Sellion, and 4) Left Tragian (Figure 1.3). Their greatest importance lies in their role of linking the FARO data to the head scan, and not necessarily in defining the exact location of a subject landmark. Hence, the 4 current landmarks represent standard point locations on the face portion of the head scan. Originally, we included additional points, two at infraorbitale and two at mastoidale. These are now omitted because they did not improve the quality of the final scalp and face alignment.

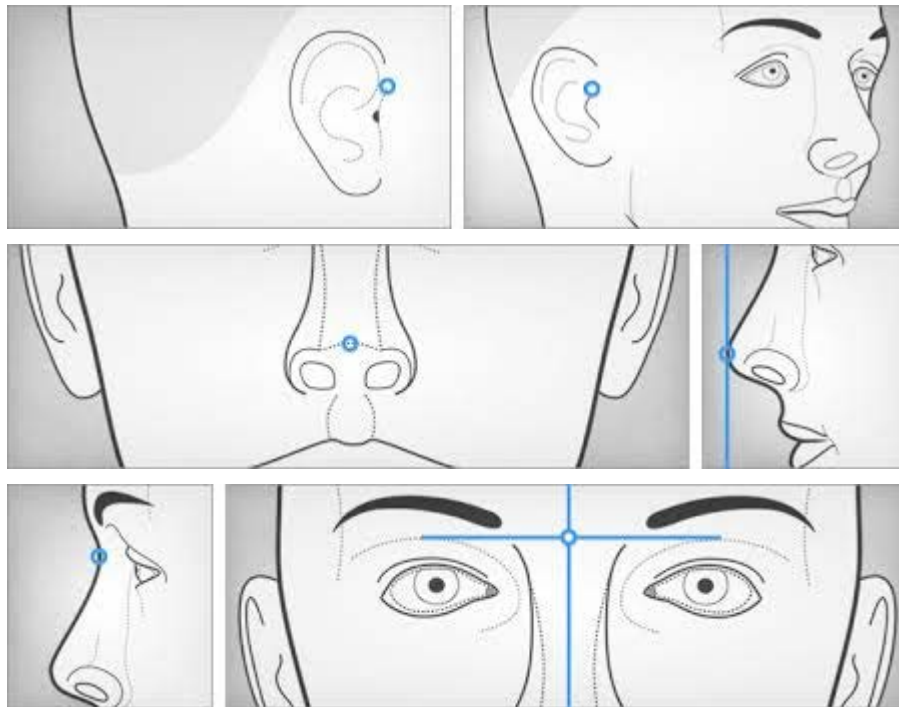


Figure 1.3: Anatomical landmark stickers placed on subject. From the top they are 1) Trignon (right side shown), 2) Pronasale and 3) Sellion.

Photos taken from FaceBase.org: Comprehensive data and resources for craniofacial researchers

FSU’s Morpheus software uses a morphometric “best fit” (i.e. scaling, rotation and translation) using these four alignment points as the alignment procedure.

3. Accuracy and Repeatability

This section reports on accuracy and repeatability of various parts of the entire scalp representation procedure.

3.1. Repeatability of a researcher digitizing landmarks on a live subject in the head fixation rig

It is impossible for a subject to sit 100% motionless, or for the data collected to be 100% accurate. So in order to investigate landmark repeatability, landmarks were digitized 10 times while a live subject was strapped into the head fixation rig. The statistics in Table 1.1, below, represent the total landmark picking error of a researcher combined with subject movement error.

Table 1.1 Researcher Repeatability on Live Subject Landmarks

	6mm Hard Probe: 3D Distances (mm) to Centroid			
	Right Trignon	Pronasale	Sellion	Left Trignon
Mean	0.77	0.71	0.92	0.90
SD	0.40	0.15	0.37	0.32
Min	0.30	0.47	0.46	0.27
Max	1.40	0.91	1.65	1.35
Range	1.10	0.44	1.19	1.08

As you can see, the mean error over the 10 trials is less than 1mm for each landmark. Some error is expected, but is decreased with 1) using the head fixation rig, 2) collector experience, 3) collector consistency, 4) conveying the importance of remaining motionless to the subject, and finally 5) making sure the subject is sitting in a comfortable position that can be maintained for up to 10 minutes.

3.2. Accuracy of the entire procedure using bald headed men and their head scans as a baseline

To best approximate a measure of accuracy for the scalp representation procedure on subjects with hair, we digitized and scanned two male subjects without hair. For each subject, five FARO digitizing trials were conducted using the 6mm Hard Probe. Since they are lacking hair, their head scans could be immediately compared to their respective digitized scalp points. Figure 1.5 shows both subjects' Artec Eva scan compared with one example data collection trial, used to generate distances to the scalp given their relative position above or below the head scan.

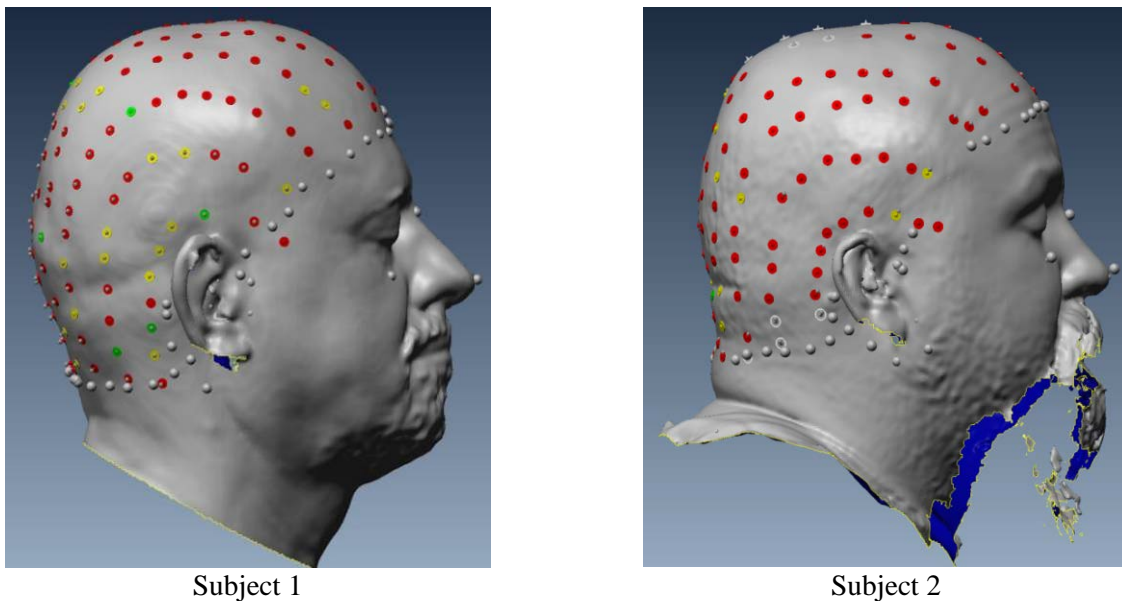


Figure 1.5: Artec scans compared to bald subjects' respective digitized scalp points

Tables 1.2 and 1.3 show the summary statistics for the ten scalps generated for each subject. The key statistics below are the reported ranges and standard deviations.

Subject 2 has trial range distances (<8mm) that were slightly larger than Subject 1. However, when compared to his range values calculated during the Preliminary Design Review, and before the final rig modifications (i.e. addition of Velcro neck strap and temple stabilization posts), his current range values have been cut in half. This is also true of his standard deviations. Prior to the rig modifications his comparison point distance standard deviations were 3-4 mm. Now they are all between 1.1 to 1.7 mm. In addition, the relative movement observed in his point data was

absent this time, most likely due to the neck strap and temple stabilizers. Subject 1 trial ranges are slightly better with all but one range under 7mm and standard deviations 1.5mm or lower.

Table 1.2. Summary Statistics of Comparison Points for Hairless Subject 1

	Subject 1						
	Valid N	Mean	Median	Minimum	Maximum	Range	Std. Dev
Scalp 1	156	-0.1181	-0.0435	-2.6620	3.9520	6.6140	1.2459
Scalp 2	157	0.6359	0.4480	-2.3720	3.8910	6.2630	1.0171
Scalp 3	163	0.3917	0.2930	-2.2700	3.7610	6.0310	1.0387
Scalp 4	152	-0.3345	-0.4700	-3.3390	3.9330	7.2720	1.7756
Scalp 5	171	0.9146	1.0110	-2.1660	3.9310	6.0970	1.1576

Table 1.3. Summary Statistics of Comparison Points for Hairless Subject 2

	Subject 2						
	Valid N	Mean	Median	Minimum	Maximum	Range	Std. Dev
Scalp 1	153	-1.2848	-1.4740	-3.7070	3.5290	7.2360	1.4255
Scalp 2	177	-1.0036	-1.2430	-3.6820	3.7610	7.4430	1.4403
Scalp 3	176	-1.1745	-1.1970	-3.9840	3.5960	7.5800	1.2015
Scalp 4	187	-0.9480	-1.1110	-3.8200	3.6560	7.4760	1.2454
Scalp 5	176	-1.6004	-1.6770	-3.8970	3.8990	7.7960	1.2240

It was observed that the greatest deviation from scalp points to head scan occurred in the lower neck area. For these subjects, this tissue protrudes more in the seated-upright scanning posture when compared to the points digitized while in the head fixation rig. This must be a function of the redistribution of soft tissue between the two postures.

3.3. Repeatability of the entire procedure using a female with hair

To investigate repeatability, one female subject was selected to quantify repeatability of the process resulting in a scalp shape. Her scalp was digitized three times with the same hair parts in place. These three sets of digitized points were then aligned using the anatomical landmarks associated with each scalp point cloud. Color distance maps, indicating differences between the scalp shapes report ranges of -3mm to +3mm. When all three were compared to the mean shape, color representation showing +/- 1mm deviation were dominant on the color map. These accuracy measures were calculated using the same program we used to collect the raw data (i.e. polyworks) and the Artec Eva photogrammetric scanner that produces the initial head scan.

APPENDIX II: Basic Instruction Manual

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1. **HARDWARE and ENVIRONMENT CHECKLIST**

- The neck strap, temple stabilizers, and chin rest are all adjustable
- The chin rest is adjustable up/down and tilts fore/aft
- A chair provides additional up and down adjustment
- Clamp head fixation rig to a stable surface – i.e. a sturdy table or workbench
- Securely attach FARO arm to head fixation rig, using the mounting ring.
- Make sure the data collector can easily move around the subject to collect points
- Make sure the collector can reach the top and back of a subject's head with FARO Arm
- Connect the power supply, turn on the FARO Arm, and plug the USB cable into computer
- Make sure the data collector can *see and hear* the audible point collection clicks from the computer as they collect data
- Make sure the chosen probe tip is accurately calibrated. Instructions for probe calibration can be found by clicking on the “probing options” icon at the bottom of the screen when Polyworks IMInspect project is open.

2. **COMPUTER and SOFTWARE CHECKLIST**

- After verification of calibration, open Polyworks, open IMInspect workspace file
- Select the project in which empty features have been set up for reference points and polyline
- After project is open, before data collection begins, select “Save Project As” under the File drop-down menu. Save each file with Subject name and date (i.e. Whitehead 11_12_2013).

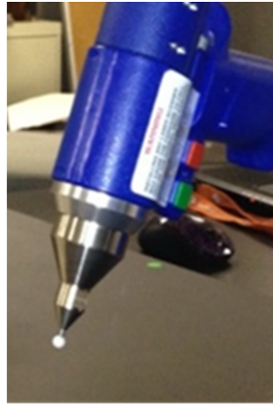
3. **SUBJECT PREPARATION**

- Briefly explain the process to the subject, including the hair parting process, how to situate themselves in the chin rig, and a description of how the data collector will be taking digital measurements on reference landmarks and scalp. Emphasize needing the subject's assistance in holding as still as possible, which is most easily done when the subject can relax into the head fixation rig.
- The entire data collection should take between a half hour and an hour from start to end. Subjects need to be aware that they can discontinue participation at any time. Inform them to let you know if they are uncomfortable or do not wish to continue.

- **MAKE SURE THEY READ AND SIGN THE REQUIRED CONSENT FORMS BEFORE PROCEEDING.**

Some things to remember when using the standard 6mm Hard Ball Probe

1. It does not automatically deflect on a surface, each point needs to be taken manually
2. The data collector needs to be careful about pressing the probe tip into subjects, causing soft tissue deformation, subject discomfort, and possible head movement.
3. The data collector also needs to be careful about taking a point with the probe tip not being in contact with the subject. Hitting the button will take data points whether you are in contact with the scalp or not.
4. Use caution as this probe tip can easily get caught in hair if dragging across the scalp.
5. It is also tightly mounted probe on the FARO arm, it will not detach if struck or dropped.



4. REFERENCE LANDMARKS

All collections (FARO and Face scan) should include the four reference landmarks.

- 4.1** Using a makeup pencil, place a small mark on the subject, identifying the four landmarks, and giving the data collector a target.
- 4.2** Palpate the areas described and carefully place reference landmark in correct location, ensuring they will stay in place for both the FARO digitizing and the Eva Face scan.

- **Tragion (Right)** – The superior point on the juncture of the cartilaginous flap of the ear with the head
- **Pronasale** – The point of the anterior projection of the tip of the nose
- **Sellion** – The point of the deepest depression of the nasal bones at the top of the nose
- **Tragion (Left)** – The superior point on the juncture of the cartilaginous flap of the ear with the head

5. ANTHRO MEASUREMENTS

Collect four Anthropometric measurements (with hair down)

Measure	Description	cm
Head Length	The distance from the glabella landmark between the brow ridges to opisthocranium. Measured with calipers.	
Head Breadth	The maximum horizontal breadth of the head above the ears. Measured with calipers.	
Circumference	The maximum circumference of the head above the supraorbital ridges and ears. Measured with steel tape.	
Trigion to Top of Head (TTOH)	The vertical distance between the right trigion landmark and the horizontal plane tangent to the top of the head. Measure with anthropometer.	

6. SCANNING

Scanner and software used is to be determined. In order to get a 3D scan with the Artec Eva scanner, the data collector needs a space in which to be able to move 360° around the sitting subject. Subjects should have the back of their neck visible (have ladies pull long hair into a low bun for example) as well as all of the reference/alignment anatomical landmarks. Ideally, their head-neck posture should be similar to their position in the chin rig, a neutral upright sitting position.

- 6.1 After marking reference landmarks and taking anthro measurements, subject should pull hair back and secure it similarly to how they would wear it in a helmet.
- 6.2 Place a bald cap over their hair, including over a bun (if necessary), making sure the cap does not cover the ears or the reference landmarks.
- 6.3 Collect 360° scan of subject sitting still, in an upright posture similar to how their head will be placed in the chin rig.

7. HAIR PARTING (Need: comb, butterfly hair clips of varying sizes, hair ties)

- 7.1 Begin by making a center part down the sagittal plane, roughly separating the quantity of hair into two large equal sections. Secure the left section of hair with a hair tie.
- 7.2 Focusing on the right section of hair, make another part to the right of the center, just over an inch in width. Ensure that this width will allow you to make four uniform parts on the right side of the head, from center to above the ear.

7.3 For each of the four small sections, beginning towards the forehead and working toward the nape of the neck, twist small sections of hair back and clip into place. You should be able to see the scalp between the hair sections. Secure each part with a hair tie before proceeding to the next section of hair.

7.4 Repeat Steps 2 and 3 on the left side of the scalp. When finished, you should have 9 parts total. Examples below:



4.5 Free Form

- Choosing not to part may be best for hair that is straight and fine with little to no texture (allows a brush to pass through quickly without catching) that is too short for parting.
- This method also works well with bald men, or men with short hair.
- Instead of following part lines, place an easily removable marking as a reference guide for each part line.

8. PROCEDURE PREPARATION CHECKLIST

- Allow seated subject to momentarily place their head against the brow strap in order to indicate their preferred chin rest height and angle. They should be able to lean forward from their normal sitting position, without having to flex or extend their neck.
- Adjust the seat and chin rig to accommodate for participant comfort, height, and appropriate posture.
- Make sure the chin rest base locks are tightened so it does not move during data collection.
- With the chin rest in the lowest position and temple stabilizers fully retracted, instruct subject to lean forward, placing their forehead against the brow-strap. The brow strap should be across forehead, slightly above their eyebrows.

- While they maintain this position, adjust the chin-rest up until their chin is resting on it with their brow still placed against the strap. They will have to specify when it is an appropriate height, with their chin comfortably resting while keeping their brow-bone across the strap.
- Slide the left-side brace (white plastic collar, with Velcro attached) up to hold chin rest stable.
- Make sure that the subject's head/neck posture is not forced into extension. It should be similar to the posture assumed during the face scan.
- Have them extend their arms onto aluminum plate in front of them, hands clasped, resting upper body weight on forearms. Something soft (i.e. foam padding) may be placed on aluminum plate for them to rest their arms on.
- Slowly turn temple stabilizers clockwise simultaneously, in order to extend both toward the subject's scalp. Again, your subject will need to give verbal confirmation when it is appropriately snug. Adjust to comfort. They are not intended to be so tight against the scalp that they cause discomfort and excess tissue deformation.
- Fasten the Velcro strap around the nape of the neck, under the hair, to the Velcro on the right side of chin rest. The strap placed around the back of the neck should also be snug, but not so tight as to cause soft tissue deformation and subject discomfort.
- Instruct subjects to stay as still as possible. There should be no talking, smiling, laughing, gum chewing, etc. Tell them to relax and let their weight hold them still and to inform you if they become uncomfortable.

Preventing movement is the responsibility of both the subject and the data collector. Do not use the chin rig as a hand rest during data collection. However, some light contact may be useful in steadying the hand holding the probe. Avoid bumping into the subject or their seat. Also use care when restoring the FARO Arm to resting position. Letting it hang/swing back into place can shake the setup and/or damage the probe tip.



9. DATA COLLECTION – Reference landmarks and Polyline

- 9.1** Check that “Object Measurement Confirmation” is checked. This is found under Probing Options (see Figure 12 for icon location).
- 9.2** After opening designated workspace, highlight **ALL** empty point features in tree, including reference landmarks and polyline, right click to display the menu and select “Probe Measured” (Figure 20).
- 9.3** Gently pick up the Faro arm and collect reference points in order (by touching the center of the stickers placed at the reference landmarks and pressing the green button on the Faro grip). The point should be taken while making the lightest possible contact with landmark or scalp.
1. Right Tragion
 2. Pronasale
 3. Sellion
 4. Left Tragion
- 9.4** Inform the subject before you take reference points on their face, they may close their eyes if uncomfortable

After collecting each reference point, press the green button on Faro arm grip to confirm

- 9.5** Polyworks will progress automatically from reference landmarks to collecting a polyline. Since landmark collection ends on the subject’s left, it is most convenient to stay on this side and begin the polyline in the center of their forehead, above the brow strap. Use the forehead-sticker as a starting point.
- 9.6** Continuing counter-clockwise from forehead to left Tragion, under the ear and around the back of the neck. Follow the hairline around to above right ear/tragion and back to center of forehead, but do not go past sticker starting point. Polyline points do not need to be confirmed on the Faro arm grip.
- 9.7** When data collector has made it all the way around back to the center front forehead, hit the red button quickly and then the green button to complete the polyline collection.

Remember!

For reference landmarks, polyline, and scalp points, the last data point(s) collected may be cancelled by depressing the back red button. The computer will make a sound to indicate how many points will be deleted, depending on how long the button is held down. Be careful as to not delete more than intended.

10. DATA COLLECTION – Scalp Digitizing

- 10.1 In the data tree, right click on Data -> Probe -> Surface Point Clouds.
 - a. No reference object
 - b. Mode-Single
- 10.2 Starting on the part directly above the right ear, tap the probe tip directly on the visible scalp, starting from the forehead working back toward the base of the neck.
- 10.3 Follow hair parts forward to back, right to left across scalp, pausing briefly between each point.
- 10.4 Make sure to check the screen for missing scalp data first, then allow the subject to sit back from chin rig.
- 10.5 When scalp digitizing is complete, save the workspace and project under Subject name and date. Wipe chin rest and brow strap clean with alcohol wipe.
- 10.6 A second set of landmarks can be collected to confirm that the subject had little to no movement during data collection. These will not be used in data processing.

Remember!

If a point is collected in contact with a surface other than the scalp, the last data point(s) collected may be cancelled by pressing the back red button. The computer will make a sound to indicate how many points will be deleted, depending on how long the button is held down. Be careful as to not delete more than intended.

Note for Subjects with very short (or no) hair

If using the 6mm Hard Ball Probe and not parting the subject's hair, the data collector will need to follow arbitrary "part lines" in order to collect information comparable to parted hair. Do this by gently dragging through hair while maintaining light contact with the subject's scalp. Points should be taken manually by hitting the green button.

11. DATA PROCESSING

After scalp digitization or right before the point files are exported from Polyworks IMInspect, to spin the point cloud in 3D and make sure there are no obviously erratic points. If there are, delete them.

Three files need to be created separately for the boundary "hairline points, and the scalp points by exporting this data from the Polyworks IMInspect file.

- The named anatomical landmark file is created by highlighting all of the named landmark points under Features in Tree View, right click and export as a text file. Select the option for "Points + Names" under Template.
- The hairline points file is created by highlighting the polyline under Features in Tree View, right click and export as a text file. Select "Points Only" for the Template option
- The scalp points will be saved by highlighting the "probed surface 1" object under "Data" in Tree View. Right click on "probed surface 1," and then export as point cloud, name it and save it as a text file.

APPENDIX III: Data Processing:

USING POLYWORKS, ARTEC STUDIO, MESHLAB, & MORPHEUS_INFOSCITEX

I. Create individual subject folder

- a. Work from this folder, all the data needed to generate scalp will be saved here
- b. Copy Atlas_edited.ply file and Atlas_edited_landmarks.txt file into folder

II. Export Polyworks data

a. Landmarks

- i. Under Features, select all 4 landmarks and right click
- ii. Select export as text file
- iii. Naming convention = "Last Name"1_faro_landmarks.txt

b. Hairline

- i. Also under Features, select hairline and right click
- ii. Select export as text file
- iii. Naming convention = "Last Name"1_faro_hairline.txt

c. Scalp "Cloud"

- i. Under Data, select "probed surface" 1 and right click
- ii. Select export as point cloud
- iii. Naming convention = "Last Name"1_faro_scalp.txt

III. Artec Studio

a. Point Picking

- i. Scan and go through steps to combine images and add back texture
- ii. On left, click on Measures icon, and then select Linear Measures icon, click Next
- iii. Select landmark points in order by left clicking
- iv. Export to folder as "Last Name"1_landmarks.csv
- v. Next open the csv file in Excel, copy XYZ coordinates and paste into black notepad, deleting extra spaces at the beginning of each line, save as "Last Name"1_landmarks.txt

b. Export Mesh

- i. Under File, click on Export Mesh
- ii. Naming convention = "Last Name"1_eva.ply
- iii. Close scan and exit Artec

IV. File Consolidation

- a. Open "Last Name" Folder
- b. Ensure all 7 files are present
 1. Atlas_edited.ply
 2. Atlas_edited_landmarks.txt
 3. "Last Name"1_faro_landmarks.txt
 4. "Last Name"1_faro_hairline.txt

5. "Last Name"1_faro_scalp.txt
6. "Last Name"1_landmarks.txt
7. "Last Name"1.ply

V. Morpheus_Infoscitex

a. Set Prototype

- i. After opening Morpheus_Infoscitex, go to Infoscitex drop-down menu -> Set Prototype
- ii. Select Atlas_edited.ply

b. Data Merge

- i. Go to Infoscitex drop-down menu -> Faro Data Merge
- ii. Select "Last Name"1.ply
- iii. Three files will automatically be output into data folder
 1. "Last Name"1_out_face.ply
 2. "Last Name"1_out_scalp.ply
 3. "Last Name"1_out_merged.ply

VI. Meshlab for Hole Filling

- a. Import Mesh – select output scalp file "Last Name"1_out_merged.ply
- b. Use dropdown boxes to select "Filters" -> "Remeshing, Simplification, and Reconstruction" -> "Surface Reconstruction: Poisson"
- c. Use the following settings:
 - i. Octree Depth: 12
 - ii. Solver Divide: 12
 - iii. Samples per Node: 1
 - iv. Surface Offsetting: 1
- d. Export Mesh as "Last Name"1_out_merged_holes_filled.ply
- e. Output from Meshlab can be edited in Polyworks (3-5 minutes per subject) to match expected smoothness and scalp/face representation to an agreed upon standard.