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RESEARCH ARTICLE

REVISED Accuracy of linear measurements obtained from stitched cone beam computed tomography images versus direct skull measurements [version 2; peer review: 2 approved]

Doaa Ahmed Fouad Hamed [1], Mostafa Mohamed El Dawlatly[2], Sahar Hosny El Dessouky[1], Reham Mohamed Hamdy[1]

[1]Oral and Maxillofacial Radioalogy Department, Faculty of Dentistry, Cairo University, Cairo, Egypt
[2]Orthodontic Department, Cairo University, Cairo, Egypt

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Abstract
Background: To assess whether the linear measurements obtained from stitched cone beam computed tomography (CBCT) images were as accurate as the direct skull measurements.
Methods: Nine dry human skulls were marked with gutta-percha at reference points to obtain Twenty-two linear measurements on each skull. Ten measurements in the cranio-caudal plane, two measurements in the antero-posterior plane, and ten measurements in the medio-lateral plane. CBCT linear measurements obtained using stitching software were measured and compared with direct skull measurements.
Results: The absolute Dahlberg error between direct linear measurements and linear measurements on stitched CBCT images ranged from (0.07 mm to 0.41 mm). The relative Dahlberg error ranged from (0.2% to 1.8%). Moreover, Intra-class Correlation Coefficient (ICC) ranged from (0.97 to 1.0) indicating excellent agreement.
Conclusion: Stitched CBCT linear measurements were highly comparable to the direct skull measurements using a digital caliper.

Keywords
Cone beam CT, linear measurements, accuracy, direct measurements, field of view, stitched images.

Open Peer Review

Reviewer Status ✔ ✔

	Invited Reviewers 1	2
version 2 (revision) 02 Mar 2020	✔ report	
version 1 07 Feb 2019	? report	✔ report

1 **Luca Fiorillo**, University of Messina, Messina, Italy

2 **Pathawee Khongkhunthian**, Chiang Mai University, Chiang Mai, Thailand

Any reports and responses or comments on the article can be found at the end of the article.

Corresponding author: Doaa Ahmed Fouad Hamed (doaafouad_84@hotmail.com)

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REVISED **Amendments from Version 1**

A new co-author has been added:

Mostafa Mohamed El Dawlatly MSc., MOrth RCS(Ed), PhD, who was involved in setting the measuring protocol on the skulls, taking the study photos and in writing the article manuscript.

Any further responses from the reviewers can be found at the end of the article

Introduction

The use of cone beam computed tomography (CBCT) machines in dentistry started in the second half of the 1990s[1]. Now, CBCT is extensively used in the dental field for implant planning, in endodontics, maxillofacial surgeries and orthodontics[2].

In the field of orthodontics, analysis of cephalometric radiographs requires accurate identification of specific landmarks for precise measurements between these landmarks[3]. As a consequence, the small field of view (FOV) CBCT systems available in small clinics cannot yet satisfy the needs of maxillofacial surgeons or orthodontists[4]. Thus, visualizing all of these landmarks on the same scan is not always possible[5].

In order to compensate for this shortcoming, small FOV images can be scanned and then fused together to produce a single large FOV image. However, there are few data to show whether this fused image is as precise as a single image of the whole area of interest[4,6].

Therefore, the aim of the current study was to assess the diagnostic accuracy of stitched CBCT linear measurements versus direct measurements on skulls.

Methods

The current study was conducted on nine dry human skulls obtained from the Anatomy department, Faculty of Medicine, Cairo University to avoid the exposure of living humans to unnecessary radiation doses. 26 anatomical landmarks were identified on each skull (Table 1). Gutta percha cones (GE16121542, META BIOMED) were glued and used as radiopaque markers (Figure 1–Figure 3).

22 linear measurements were taken and recorded using a high precision sliding digital caliper (6400192, Allendale Electronics Ltd, Hertfordshire, UK). Ten measurements in the cranio-caudal plane (Table 2), two measurements in the antero-posterior plane (Table 3), and ten measurements in the medio-lateral plane (Table 4). 22 direct linear measurements were measured and were considered to be the gold standard in the study (Figure 4–Figure 6).

For soft tissue simulation, the skulls were covered with 20 layers of pink modelling wax (1mm thick each) (Tenatex eco, Kemdent) to achieve an average of 14–16 mm wax thickness[7].

The skulls were stabilized in the Planmeca ProMax 3D Mid CBCT machine using a wooden stand passing through the foramen magnum and were oriented using the laser beams (Figure 7). Three consecutive FOVs were scanned: two scans each of the

Table 1. Showing the twenty-six anatomical landmarks identified on each skull.

Nasion (N)	The most anterior median point on the fronto-nasal suture.
Anterior nasal spine (ANS)	The most anterior median point (tip) of the anterior nasal spine of the maxilla.
Posterior nasal spine (PNS)	The most posterior median point (tip) of the posterior nasal spine of the maxilla.
A -point (A)	The point of maximum concavity in the midline of the alveolar process of the maxilla.
B-point (B)	The point of maximum concavity in the midline of the alveolar process of the mandible.
Menton (Me)	The most inferior midpoint of the chin on the outline of the mandibular symphysis.
Zygomatic foramen (ZYF) R&L	A small aperture on the convexity of the malar surface of the zygomatic bone near its center.
Condyle (Co) R&L	The most superior median point of the right and left condylar head.
Mandibular gonion (Go) R&L	Most posterior and inferior point of the curve between the body and ascending ramus on the right and left sides of the mandible.
Medial orbital wall (MOR) R&L	Point on the middle of the medial wall of the right and left orbits.
Lateral orbital wall (LOR) R&L	Point on the middle of the lateral wall of the right and left orbits.
Infra-orbital foramen (ORF) R&L	Foramen located below the infra-orbital margin of the right and left orbits.
Greater palatine foramen (GP) R&L	An aperture on the right and left postero-lateral aspects of the hard palate.
Mental foramen (MF) R&L	An aperture on the buccal surface of the mandible in the area of the mandibular premolars teeth on the right and left sides.
Anterior ramus (AR) R &L	Point on the middle of the anterior border of the right and left ramus.
Posterior ramus (PR) R&L	Point on the middle of the posterior border of the right and left ramus.

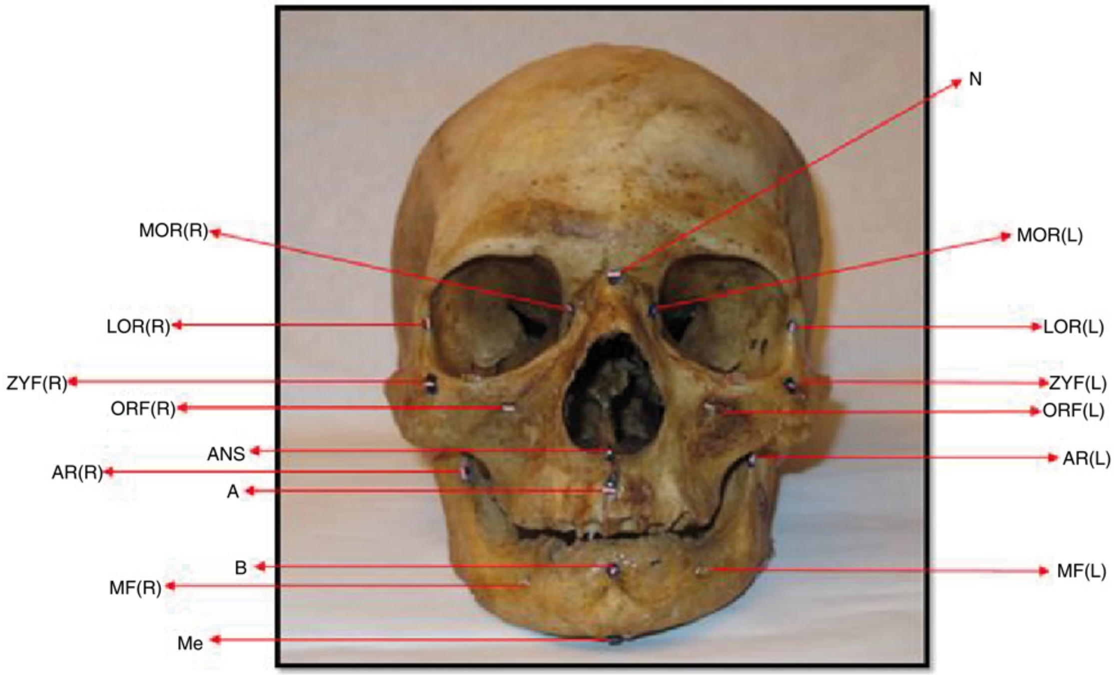

Figure 1. **A photograph showing the frontal aspect of the skull.**

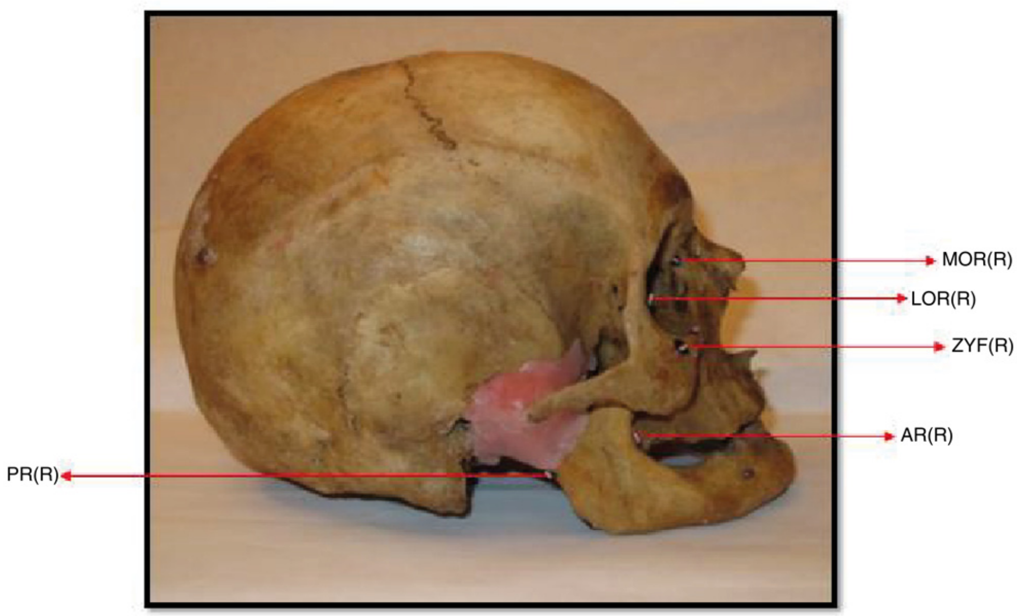

Figure 2. **A photograph showing the lateral aspect of the skull.**

size 160 ×60 mm (single arch) for the mandible and the maxilla separately (Figure 8 and Figure 9) and one scan with a FOV size 200 ×100 mm for the upper third of the face (Figure 10). Each one of the three FOVs was scanned separately using a voxel resolution 0.2 mm, 90 kVp and 10 mA, then stitching was performed using Romexis software (Planmeca Romexis Viewer Launcher 4.5.0.R) creating one large volume (Figure 11). After completion of the stitching procedure the linear measurements were obtained from the stitched CBCT images for a later comparison with the gold standard (Figure 12 and Figure 13).

Statistical analysis

Statistical analysis was performed on SPSS (version 17). For assessment of the agreement between all measurements with

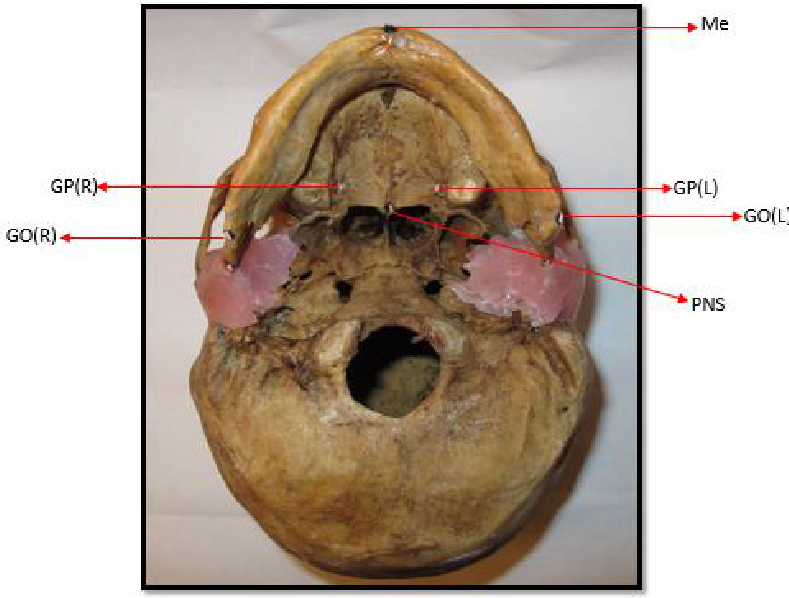

Figure 3. A photograph showing the skull base.

Table 2. Showing cranio-caudal linear measurements.

N-ANS	Nasion to anterior nasal spine.
N-A	Nasion to A-point.
N-B	Nasion to B-point.
N-Me	Nasion to menton.
ANS-A	Anterior nasal spine to A-point.
ANS-Me	Anterior nasal spine to menton.
B-Me	B-point to menton.
ORF(R)-MF(R)	Right infra-orbital foramen to right mental foramen.
ZYF(R)-MF(R)	Right zygomatic foramen to right mental foramen.
CO(R)-GO(R)	Right condyle to right gonion.

Table 3. Showing antero-posterior linear measurements.

ANS-PNS	Anterior nasal spine to posterior nasal spine.
AR(R)-PR(R)	Right anterior ramus to right posterior ramus.

Table 4. Showing medio-lateral linear measurements.

CO(R)-CO(L)	Right condyle to left condyle.
GO(R)-GO(L)	Right gonion to left gonion.
GP(R)-GP(L)	Right greater palatine foramen to left greater palatine foramen.
ORF(R)-ORF(L)	Right infra-orbital foramen to left infra-orbital foramen.
ZYF(R)-ZYF(L)	Right zygomatic foramen to left zygomatic foramen.
MOR(R)-MOR(L)	Right medial orbital wall to left medial orbital wall.
LOR(R)-LOR(L)	Right lateral orbital wall to left lateral orbital wall.
MF(R)-MF(L)	Right mental foramen to left mental foramen.
AR(R)-AR(L)	Right anterior ramus to left anterior ramus.
PR(R)-PR(L)	Right posterior ramus to left posterior ramus.

R – right, L - left

Figure 4. A photograph showing direct linear measurement from Nasion to Anterior nasal spine.

Figure 5. A photograph showing direct linear measurement from right Zygomatic foramen to right Mental foramen.

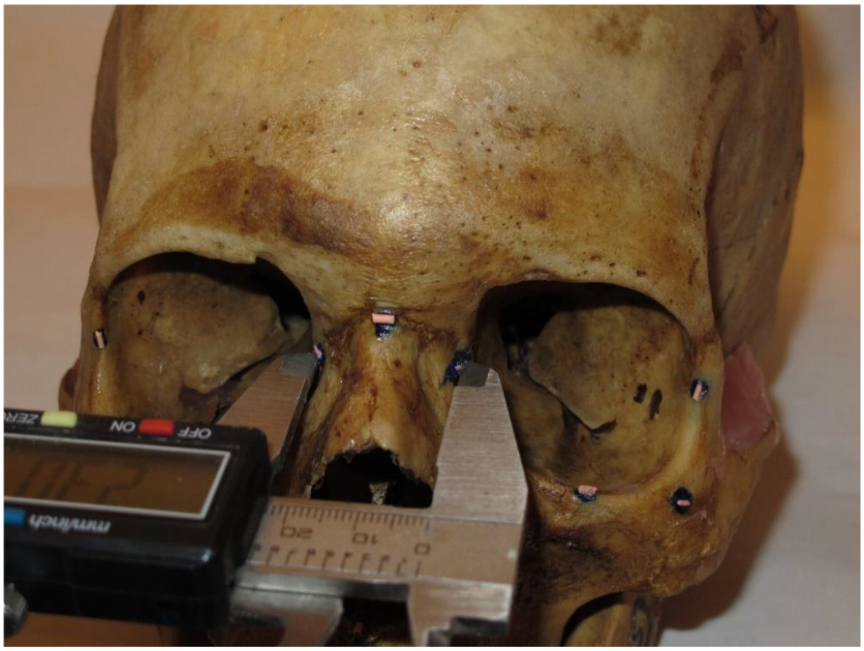

Figure 6. A photograph showing direct linear measurement from right Medial orbital wall to left Medial orbital wall.

Figure 7. A photograph showing the skull centralized within the CBCT machine in the proper position.

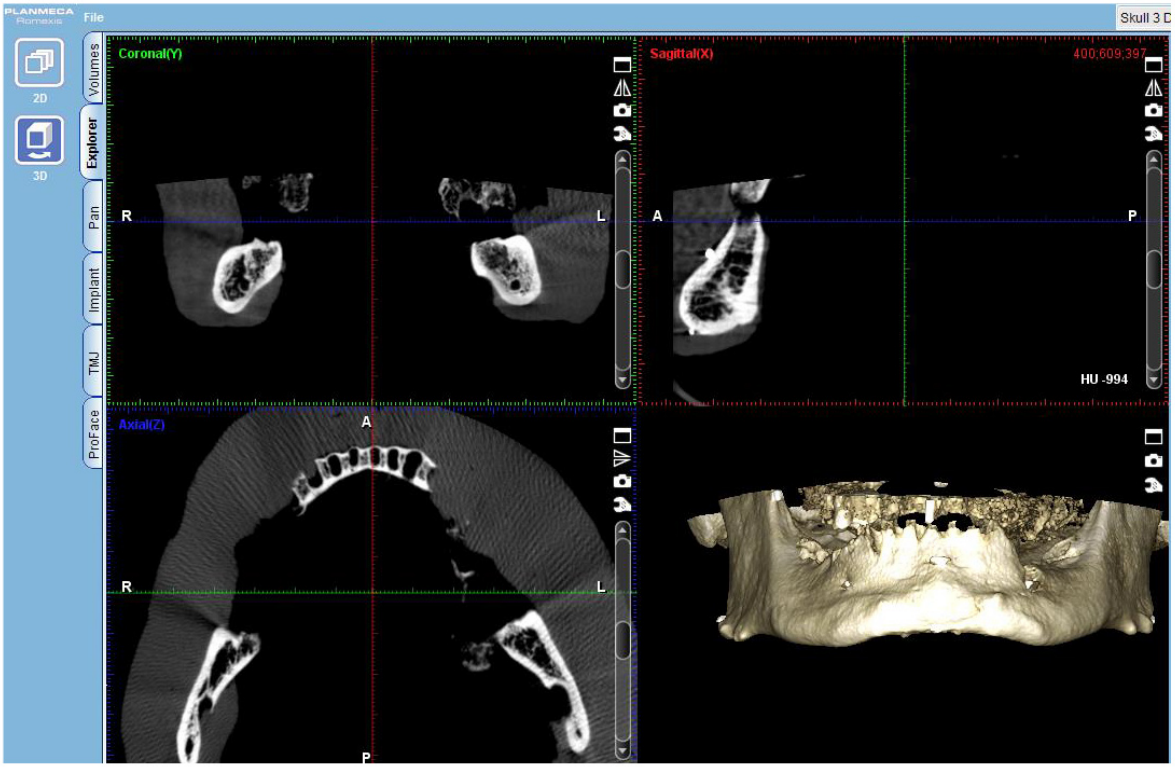

Figure 8. **First field of view showing the mandible.**

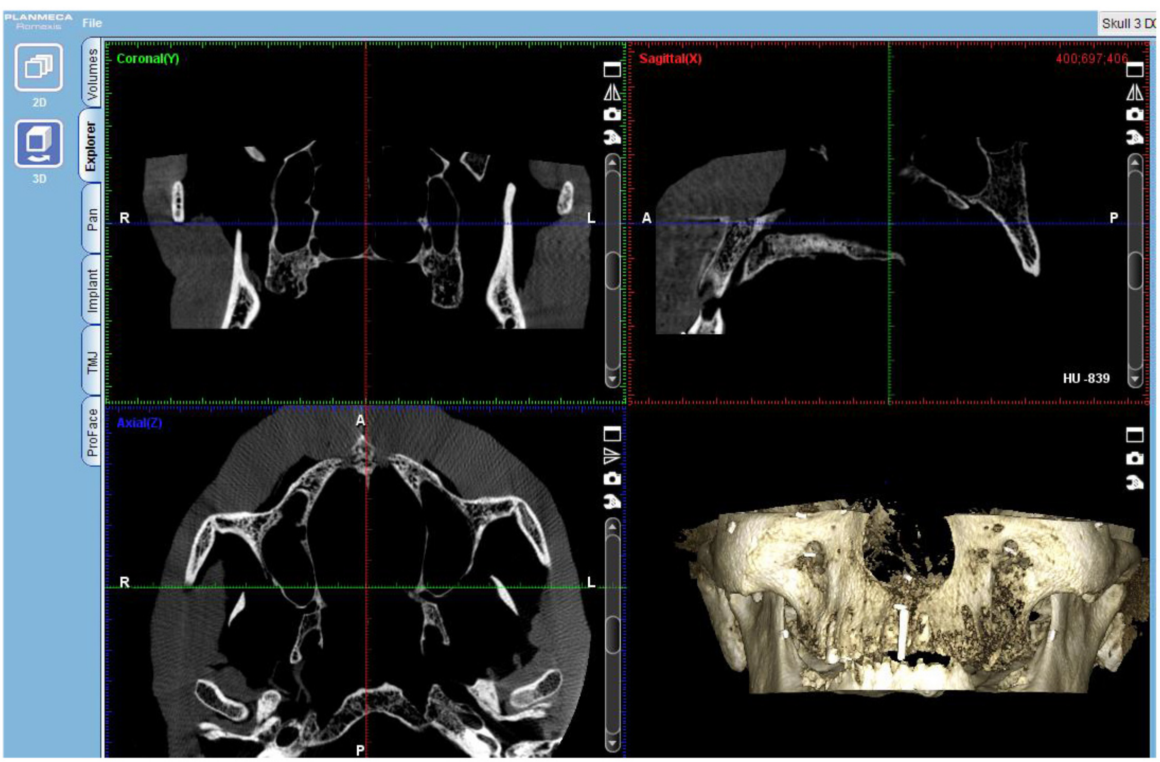

Figure 9. **Second field of view showing the maxilla.**

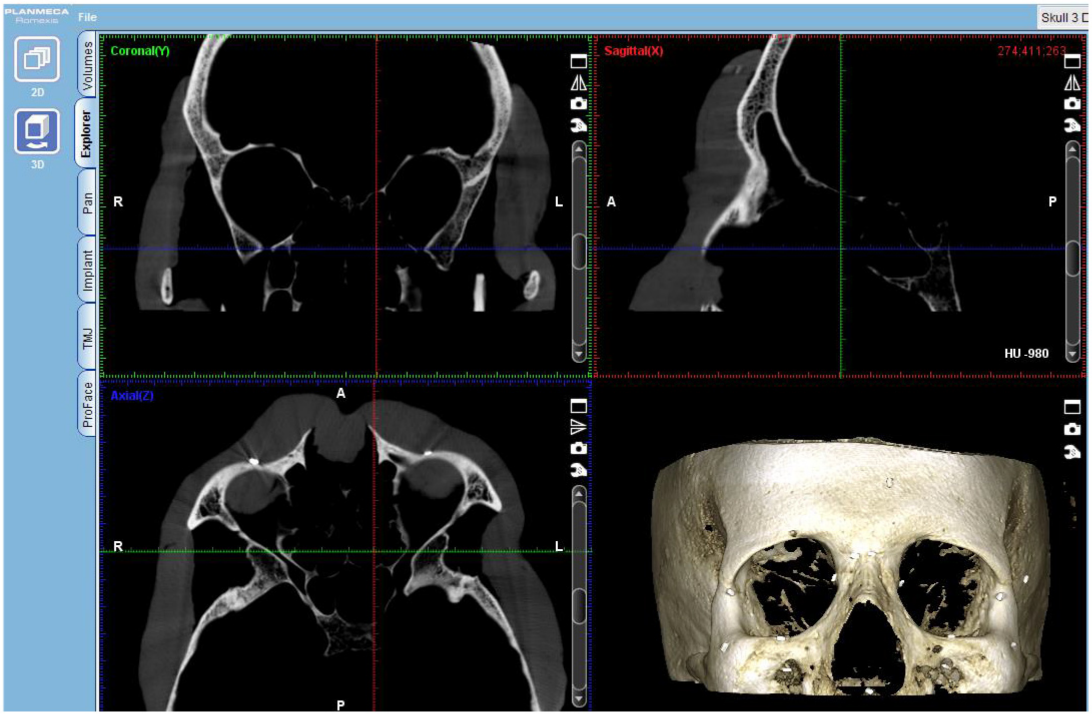

Figure 10. **Third field of view showing the upper third of the face, orbits, frontal bone.**

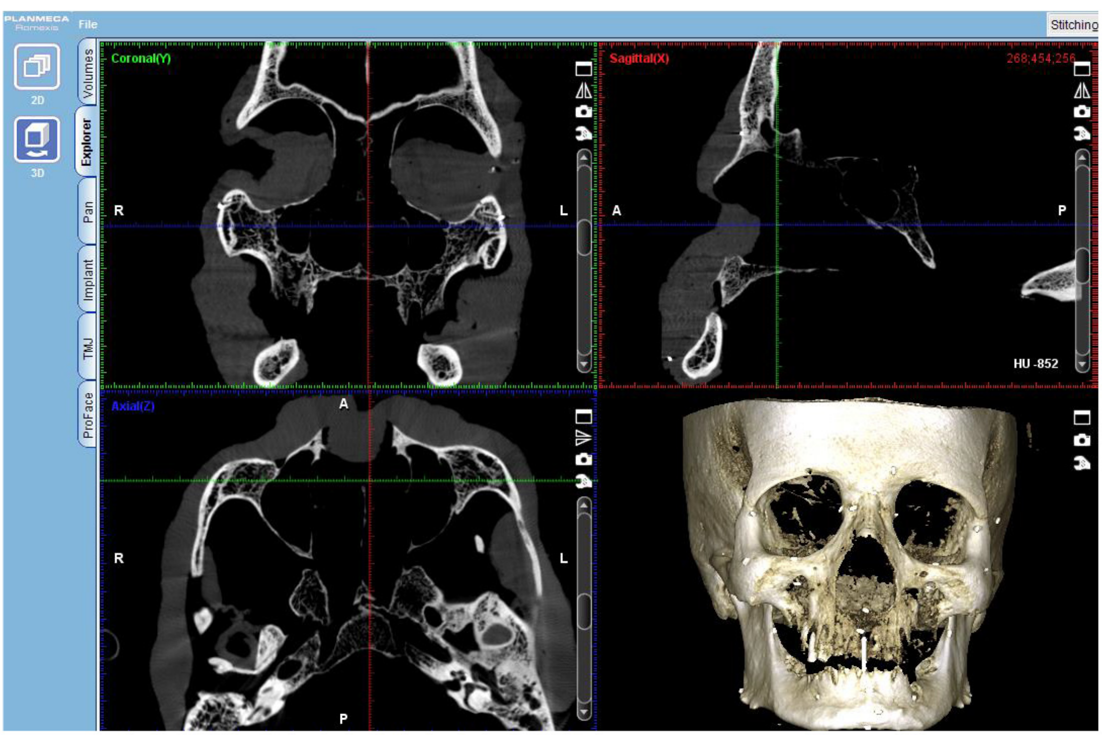

Figure 11. **The final image showing the stitched three small fields of view into a single large one.**

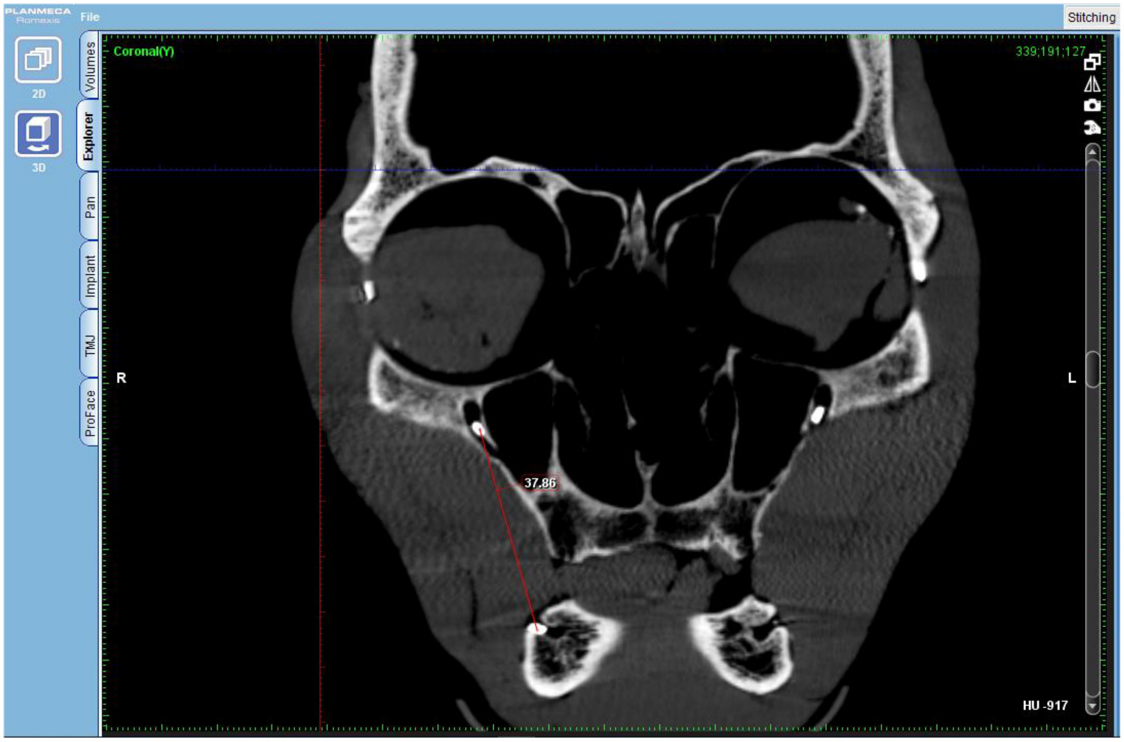

Figure 12. **Coronal cut showing linear measurement of Orbital foramen (right)-Mental foramen (right) on a stitched image.**

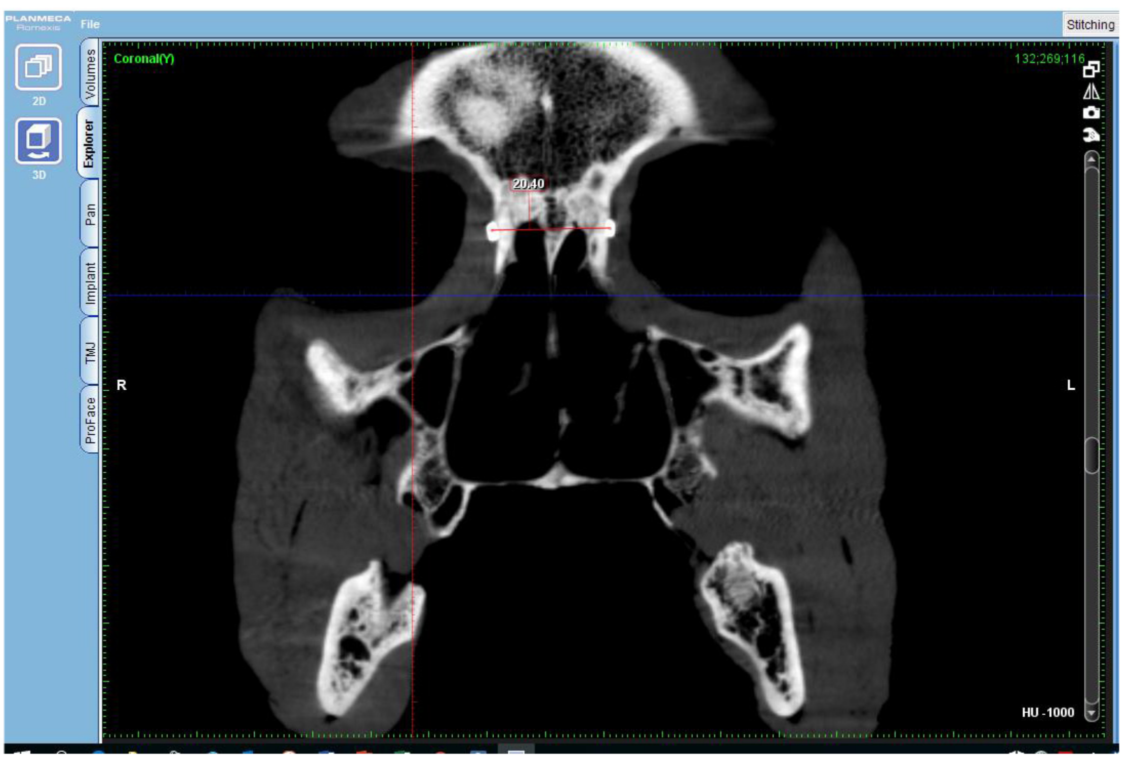

Figure 13. **Coronal cut showing linear measurement of Medial orbital wall (right)-Medial orbital wall (left) on a stitched image.**

the reference method, Dahelberg error (DE), and Relative Dahelberg Error (RDE) were used together with Intra-class Correlation Coefficients (ICC) including the 95% confidence limits of the coefficient calculated assuming analysis of variance two-way mixed model ANOVA with absolute agreement on SPSS. To measure and quantify the size of the differences, Bland and Altman 95% confidence Limits of Agreements (LOA) were applied.

Results

Error assessment of linear measurements conducted on stitched CBCT images versus direct skull measurements (the gold standard) (Table 5)

The results of the current study showed that, the difference between the mean of the direct linear measurements and the mean of the linear measurements conducted on the stitched CBCT images ranged from (-0.25 mm to 0.5 mm), the

Table 5. Comparing direct linear measurements and measurements conducted on stitched CBCT images.

								Bland & Altman Limits of Agreement (LOA)		Intra-class Correlation Coefficient		
Linear Measurements	Direct/ Stitched	Mean	SD	Dahlberg Error (DE)	Relative Dahlberg Error (RDE)	Mean of Difference (Reference - Stitched)	SD of the Difference	95%confidence limits			95%confidence limits	
								Lower	Upper	ICC	Lower	Upper
N-A	Direct Reference	56.71	4.35	0.21	0.4%	-0.11	0.30	-0.70	0.47	0.999	0.995	1.000
	Stitched	56.82	4.35									
N-ANS	Direct Reference	49.85	4.11	0.25	0.5%	-0.15	0.33	-0.81	0.50	0.998	0.992	1.000
	Stitched	50.00	4.20									
N-Me	Direct Reference	96.91	9.44	0.27	0.3%	0.21	0.33	-0.45	0.86	1.000	0.998	1.000
	Stitched	96.70	9.54									
N-B	Direct Reference	77.91	7.56	0.29	0.4%	-0.25	0.34	-0.92	0.42	0.999	0.995	1.000
	Stitched	78.16	7.51									
ANS-A	Direct Reference	7.28	1.62	0.09	1.3%	-0.09	0.10	-0.29	0.10	0.998	0.983	1.000
	Stitched	7.37	1.63									
ANS-PNS	Direct Reference	52.28	3.39	0.09	0.2%	0.02	0.14	-0.25	0.30	1.000	0.998	1.000
	Stitched	52.26	3.39									
ANS-Me	Direct Reference	46.95	6.52	0.23	0.5%	0.00	0.34	-0.66	0.67	0.999	0.997	1.000
	Stitched	46.95	6.59									
B-Me	Direct Reference	18.88	3.13	0.15	0.8%	0.18	0.12	-0.06	0.42	0.999	0.949	1.000
	Stitched	18.70	3.17									
ORF(R)-ORF(L)	Direct Reference	53.01	5.54	0.15	0.3%	-0.04	0.23	-0.48	0.41	1.000	0.998	1.000
	Stitched	53.04	5.43									
MOR(R)-MOR(L)	Direct Reference	22.94	1.89	0.41	1.8%	0.50	0.32	-0.13	1.12	0.974	0.318	0.996
	Stitched	22.45	1.67									
LOR(R)-LOR(L)	Direct Reference	96.81	3.86	0.22	0.2%	0.05	0.32	-0.58	0.68	0.998	0.993	1.000
	Stitched	96.76	3.88									
ZYF(R)-ZYF(L)	Direct Reference	96.95	6.18	0.17	0.2%	0.11	0.22	-0.33	0.55	1.000	0.998	1.000
	Stitched	96.85	6.26									

								Bland & Altman Limits of Agreement (LOA)		Intra-class Correlation Coefficient		
Linear Measurements	Direct/ Stitched	Mean	SD	Dahlberg Error (DE)	Relative Dahlberg Error (RDE)	Mean of Difference (Reference - Stitched)	SD of the Difference	95%confidence limits			95%confidence limits	
								Lower	Upper	ICC	Lower	Upper
GP(R)-GP(L)	Direct Reference	31.60	2.69	0.15	0.5%	-0.07	0.21	-0.49	0.35	0.998	0.993	1.000
	Stitched	31.67	2.63									
ORF(R)-MF(R)	Direct Reference	46.61	5.08	0.22	0.5%	0.03	0.33	-0.62	0.68	0.999	0.996	1.000
	Stitched	46.59	5.14									
ZYF(R)-MF(R)	Direct Reference	57.56	6.70	0.15	0.3%	-0.06	0.22	-0.49	0.37	1.000	0.999	1.000
	Stitched	57.62	6.83									
CO(R)-CO(L)	Direct Reference	101.52	4.08	0.23	0.2%	-0.03	0.34	-0.69	0.63	0.998	0.993	1.000
	Stitched	101.55	3.91									
GO(R)-GO(L)	Direct Reference	94.19	8.06	0.27	0.3%	0.07	0.40	-0.72	0.86	0.999	0.998	1.000
	Stitched	94.12	8.11									
CO(R)-GO(R)	Direct Reference	58.52	6.65	0.13	0.2%	-0.01	0.20	-0.40	0.38	1.000	0.999	1.000
	Stitched	58.54	6.64									
AR(R)-AR(L)	Direct Reference	83.31	2.71	0.30	0.4%	0.04	0.45	-0.85	0.93	0.994	0.974	0.999
	Stitched	83.27	2.87									
MF(R)- MF(L)	Direct Reference	44.72	0.95	0.15	0.3%	-0.10	0.20	-0.49	0.29	0.987	0.945	0.997
	Stitched	44.82	0.95									
PR(R)-PR(L)	Direct Reference	96.32	5.30	0.38	0.4%	0.30	0.48	-0.64	1.24	0.997	0.986	0.999
	Stitched	96.02	5.14									
AR(R)-PR(R)	Direct Reference	33.07	2.48	0.07	0.2%	0.04	0.09	-0.13	0.21	1.000	0.999	1.000
	Stitched	33.03	2.48									

N – Nasion, ANS - Anterior nasal spine, PNS - Posterior nasal spine, A – A point, B – B point, Me – Menton, ZYF - Zygomatic foramen, Co – Condyle, GO – Mandibular gonion, MOR – Medial orbital wall, LOR – Lateral orbital wall, ORF – infra-orbital foramen, GP – Greater palatine foramen, MF – Mental foramen, AR – Anterior ramus, PR – Posterior ramus, R – right, L - left

positive and negative values indicating that there was no obvious pattern of over or underestimation in the stitched CBCT measurements.

Mean absolute difference of all measurements was (0.11± 0.12 mm). Bland and Altman Lower limit of agreement ranged from (-0.92 mm to -0.06 mm). Bland and Altman Upper limit of agreement ranged from (0.1 mm to 1.24 mm).

The absolute Dahlberg error between direct linear measurements and linear measurements on stitched CBCT images ranged from (0.07 mm to 0.41 mm). The relative Dahlberg error ranged from (0.2% to 1.8%). Moreover, Intra-class Correlation Coefficient (ICC) ranged from (0.97 to 1.0). (Table 5).) indicating excellent agreement.

Discussion

The smaller the scan FOV, the higher the spatial resolution of the image[8]. Stitching of small CBCT images to create a large image can be very useful to collect the needed cranio-maxillofacial data with small FOV machines[9]. Increasing the FOV can be done by automatically fusing up to three small FOVs to obtain a larger FOV[10].

CBCT "Stitching" option could be useful but whether it is precise enough to obtain accurate and reliable measurements remains doubtful[11]. Assessing the accuracy of stitched CBCT measurements is infrequently mentioned in current literature, as in the studies conducted by Kopp and Ottl; 2010, Kim *et al.*; 2012, Egbert *et al.*; 2015, and Srimawong *et al.*; 2015[5,8,10,12].

The results of the current study showed that the relative Dahlberg error ranged from 0.2% to a maximum of 1.8%. Consequently, the error was considered small and clinically non-significant as the measurement error in craniofacial imaging is considered clinically acceptable up till the value of 5%[13,14].

The results of the current study go in agreement with the study performed by Srimawong *et al.*; 2015 on 10 dry human mandibles[12]. Their results showed that, the mean absolute differences between direct measurements and stitched CBCT measurements for vertical and horizontal distances were (0.27±0.24 mm) and (0.34±0.27 mm), respectively. Their results showed that the stitched CBCT measurements were highly accurate comparable to the direct measurements.

In support of the present results, Egbert *et al.*; 2015[8] research revealed that the mean difference between the direct linear measurements and the stitched CBCT measurements was 0.34 mm with a 95% confidence interval of (0.24 to 0.44 mm). They concluded that the precision of stitched CBCT measurements allow accurate construction of implant surgical stents.

Moreover, the results of Kopp and Ottl; 2010[10] further agree with those obtained from the current study. They used an automated method to increase the FOV of CBCT images by stitching three small FOV volumes to obtain a larger FOV one. They concluded that, the stitching software was accurate in the obtained linear measurements.

On the same line of agreement, a study was performed by Kim *et al.*; 2012[5] to investigate whether images of skulls obtained by both manual and automatic stitching of three CBCT images, provided accurate measurements as those obtained by multidetector computed tomography (MDCT). The results showed that the mean difference between automatically stitched CBCT images and the reference images ranged from (-0.8944 mm to -1.0628 mm).

Conclusion

Stitched CBCT linear measurements were highly comparable to the direct skull measurements. However, a percent of error should be expected from CBCT-derived measurements.

Data availability

Underlying data is available from Open Science Framework

OSF: Dataset 1. Accuracy of Linear Measurements Obtained from Stitched Cone Beam CT Images Versus Direct Skull Measurements https://doi.org/10.17605/OSF.IO/SUTWK[15]

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http://www.doi.org/10.17605/OSF.IO/SUTWK

Open Peer Review

Current Peer Review Status: ✓ ✓

Version 2

Reviewer Report 28 April 2020

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✓ **Luca Fiorillo**
Department of Biomedical and Dental Sciences and Morphological and Functional Imaging, University of Messina, Messina, Italy

Please improve conclusion section with future perspective of this study.

Competing Interests: No competing interests were disclosed.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Version 1

Reviewer Report 13 November 2019

https://doi.org/10.5256/f1000research.19409.r55480

✓ **Pathawee Khongkhunthian**
Center of Excellence for Dental Implantology, Faculty of Dentistry, Chiang Mai University, Chiang Mai, Thailand

The comparative study between direct measurement of the skull and the stitching CBCT data obtained from different view had been well designed and performed. The statistical analysis are appropriate and sufficient to make the conclusion. The study showed the accuracy of stitching method using a commercial software.

Some of the issues should be raised in the discussion part for more information of the study.

1. The use of dry skull compared to the real clinical situation in term of soft tissue, does the soft tissue impair the clinical accuracy?

2. If comparing the measurements between the stitching technique to the large field of view in CBCT (full skull sensor), how is the accuracy?

3. The limitation of the study should be mentioned.

4. The clinical implication?

5. It should be discussed about the software used, would the results be different if the clinician used the different software?

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and is the work technically sound?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: dental implantology, biomaterial in tissue regenneration.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Reviewer Report 12 August 2019

https://doi.org/10.5256/f1000research.19409.r52211

Luca Fiorillo
Department of Biomedical and Dental Sciences and Morphological and Functional Imaging, University of Messina, Messina, Italy

This study is very interesting, and having assessed the reliability of radiographic examinations is very useful for clinical practice.

We should only understand, as a future perspective, the differences between the different devices used, or between the different exposure settings; it could be mentioned in "Discussion" section as a limitation of the study.

The work has been well done, and the results are in agreement with other studies in the literature.

- In the "Keywords" section, I recommend using Meshwords (https://meshb.nlm.nih.gov/)
- I suggest to expand the "Introduction" section: Add notes on the history of radiology in maxillofacial and oral medicine[12]. Add clinical notes on the use of three-dimensional radiographic examinations, and how these may influence rehabilitation[3]. Furthermore it is necessary to subdivide the section into two sub-sections, for example "Background" and "Aim".
- The "Methods" section should be implemented only by improving image quality if possible.
- In the "Conclusions" section, cite a future perspective of the study, and the function of this research in clinical practice.

References

1. Jobe RP, Laub DR: Combined surgical reconstruction of the maxilla and mandible for vertical disproportion.*Plast Reconstr Surg*. 1970; **46** (3): 252-5 PubMed Abstract | Publisher Full Text
2. Solow B: Computers in cephalometric research.*Comput Biol Med*. 1970; **1** (1): 41-9 PubMed Abstract
3. Cervino G, Fiorillo L, Arzukanyan AV, Spagnuolo G, et al.: Dental Restorative Digital Workflow: Digital Smile Design from Aesthetic to Function.*Dent J (Basel)*. 2019; **7** (2). PubMed Abstract | Publisher Full Text

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and is the work technically sound?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are all the source data underlying the results available to ensure full reproducibility?
Partly

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.