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Effect of skin tone on the accuracy of hybrid and passive stereophotogrammetry

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Summary *Background:* Three-dimensional (3D) surface images acquired from stereophotogrammetry are increasingly being used to plan or evaluate treatment by plastic surgeons. Stereophotogrammetry exists in active, passive, and hybrid forms. Active and hybrid stereophotogrammetry are believed to capture darker surfaces more accurately than passive stereophotogrammetry. The purpose of this study was to investigate whether skin tone has a clinically relevant effect on the accuracy of hybrid and passive stereophotogrammetry.
Materials and methods: Seven subjects with different skin tones were recruited. 3D-printed face and breast were spray-painted in six different colors, ranging from white to black. The skin tones and paint colors were objectified by measuring their melanin index. 3D photos of the subjects and 3D prints were acquired with hybrid and passive stereophotogrammetry. These 3D photos were matched with specialized software, and their geometric differences were calculated.
Results: None of the 3D photos showed a clinically relevant mean inaccuracy. On the 3D prints, hybrid stereophotogrammetry resulted in a smaller standard deviation of the inaccuracies than passive stereophotogrammetry (0.20 ± 0.06 mm vs. 0.35 ± 0.07 mm, $p < 0.001$). Passive stereophotogrammetry yielded a correlation between the melanin index of the spray paint colors and the standard deviation of the inaccuracy (Pearson's $R = 0.60$, $p = 0.04$). On human subjects, no correlation or difference in standard deviation of the accuracy was found.

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Conclusion: Skin tone does not influence the accuracy of hybrid and passive 3D stereophotogrammetry in a clinically relevant way.

Introduction

Stereophotogrammetry, or three-dimensional (3D) photography, is an imaging technique that creates a 3D surface image (3D photo) of the patient by using multiple cameras. The imaging technique is mainly used to capture images of the face or breasts in plastic, reconstructive, and maxillofacial surgery.[1-3] Compared to traditional 2D photographs, it has a major advantage that it can be used to plan or evaluate surgery in three dimensions.[4-7]

Stereophotogrammetry exists in three forms: active, passive, and hybrid stereophotogrammetry.[8] According to Lane and Harrell,[9] active stereophotogrammetry can capture darker skins and black clothing more accurately than passive stereophotogrammetry. This has potential consequences for the interpretation of volume, distance, and surface measurements performed on the 3D photos. Medical stereophotogrammetry devices from Canfield and Di3D use passive stereophotogrammetry, while 3dMD uses hybrid stereophotogrammetry. This means that the potential consequences could be relevant to clinical practice.

The accuracy of stereophotogrammetry has been investigated on mannequins,[10-12] Caucasian subjects,[13-18] and a few Asian subjects.[13] However, to our knowledge, no study investigated the effect of skin tone on the accuracy of the stereophotogrammetry. The purpose of this study was to investigate whether skin tone has a clinically relevant effect on the accuracy of 3D photos acquired with hybrid and passive 3D stereophotogrammetry.

Materials and methods

Part 1: accuracy of hybrid and passive stereophotogrammetry on 3D prints

3D models of a face and two breasts were created in 3ds Max Studio 2016 (Autodesk, New York, NY, USA) and printed with an Ultimaker 2 3D printer (Ultimaker, Geldermalsen, The Netherlands). The 3D face model was created from a 3D photo of the main researcher. The 3D breast models were created from a 3D photo of a subject who gave written informed consent to use her acquired data in this study.

To obtain a gold standard of the dimensions of the 3D prints, white light scans were acquired with an ATOS I 2 M scanner (GOM GmbH, Braunschweig, Germany; accuracy 0.02 mm). Next, the 3D prints were spray-painted in six different colors: black (RAL 9005), dark brown (RAL 8017), medium brown (RAL 8007), light brown (RAL 8001), beige (RAL 3012), and white (RAL 9016). For each spray paint color, 3D photos of the 3D prints were acquired with a VECTRA XT (Canfield, Parsippany, NJ, USA) and a 2-pod 3dMD (3dMD LLC, Atlanta, GA, USA) 3D stereophotogrammetry setup. Both systems were set up so that a 3D photo could be captured with both systems at the same moment (Figure 1). To prevent light scattering from the flash, the spray-painted 3D prints were treated with an antireflect spray (Kenro, Swindon, UK). Finally, the melanin index of each spray paint color was determined with a Dermalab Combo skin color probe (Cortex Technology, Hadsund, Denmark).

Figure 1 VECTRA-XT (middle) and 3dMD system (white camera pods on the left and right) setup. The systems are positioned in such a way that they can capture a 3D photo at the same moment.

The 3D surface images of the white light scans and corresponding 3D photos of the 3D prints were imported and matched with an iterative closest point algorithm in Maxilim software (Medicim NV, Mechelen, Belgium). Subsequently, ray casting was performed to determine the distances in millimeters (mm) between the two 3D surface images at every 3D coordinate. The distances were imported in Matlab (MathWorks, Natick, MA, USA) to calculate their distribution. The standard deviations of the distances were tested for a correlation with the melanin index by Pearson's correlation coefficient. Subsequently, the standard deviations and the accuracy of the 3dMD images were compared to those of the VECTRA-XT images with a paired t-test. All statistical analyses were performed using SPSS version 22 (IBM Corporation, Armonk, NY, USA). A p-value < 0.05 was considered statistically significant.

Part 2: differences between hybrid and passive stereophotogrammetry images of subjects

Seven female subjects with different skin tones were included in this prospective cohort study. This number was

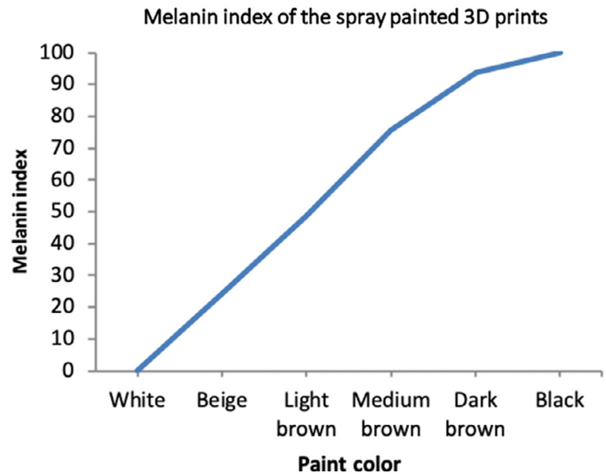

Figure 2 Melanin index of the spray-painted 3D prints. A darker color translates to a higher melanin index.

considered sufficient to yield a spectrum of skin tones. The inclusion criteria were feminine gender and age 18 years or above. The exclusion criteria were a history of facial or breast surgery. Because the number of patients with a dark skin tone in our clinic was less, the subjects were recruited by placing an advertisement on websites to facilitate the matching of voluntary subjects to scientific research. From each subject, skin tones of the cheek and both breasts were objectified by the melanin index obtained with the Dermalab Combo skin color probe. The white LEDs in the probe illuminate the skin at the probe location, while an active color sensor measures the melanin index. Each measurement was performed twice, and the results were averaged. Subsequently, 3D photos of the face and the breasts were acquired with the 3dMD and VECTRA-XT systems. By capturing the 3D photos with both devices at the same moment, the chance of a subject changing her pose between the two captures was dismissed. The subjects were requested to spread their arm horizontally and exhale normally, as this pose showed to be the most reproducible.[19]

Similar to the 3D prints, each set of 3D photos was matched and a distance map was generated. Pearson's correlation coefficient between the standard deviation of the distances and the melanin index of the spray paint colors was calculated, and a paired *t*-test was performed to determine a difference in standard deviation between 3dMD and VECTRA-XT images. A distance greater than 1.0 mm was considered to be clinically relevant. This threshold is based on preceding literature regarding the clinically relevant accuracy threshold for facial imaging.[20-22]

Results

Part 1: accuracy of hybrid and passive stereophotogrammetry on 3D prints

Figure 2 displays the melanin index of the spray-painted 3D prints. The melanin index of the spray-painted 3D prints ranged from 0 to 100. Figure 3 shows the boxplots of the distances between the 3D coordinates of the 3D photos and white light scans of the 3D-printed face and breasts. None of the 3D photos showed a clinically relevant mean distance (>1.0 mm). For the VECTRA-XT and 3dMD images, the maximum distances were 1.6 mm and 1.0 mm, respectively. For the VECTRA-XT images, a correlation was found between the standard deviation of the distances and the melanin index of the spray paint colors (Pearson's $R = 0.60$; $p = 0.04$), while no such correlation was found for the 3dMD images (Pearson's $R = 0.56$; $p = 0.06$). The mean accuracy of the 3dMD measurements was similar to the VECTRA-XT measurements (0.09±0.04 mm vs. 0.15±0.15 mm; $p = 0.13$), while the standard deviations of the 3dMD measurements were smaller (0.20±0.06 mm vs. 0.35±0.07 mm; $p < 0.001$).

Part 2: differences between hybrid and passive stereophotogrammetry images of subjects

The skin tones of the subjects from light to dark are shown in Figure 4. Because one subject did not give informed consent to use her images in publications about this study, only

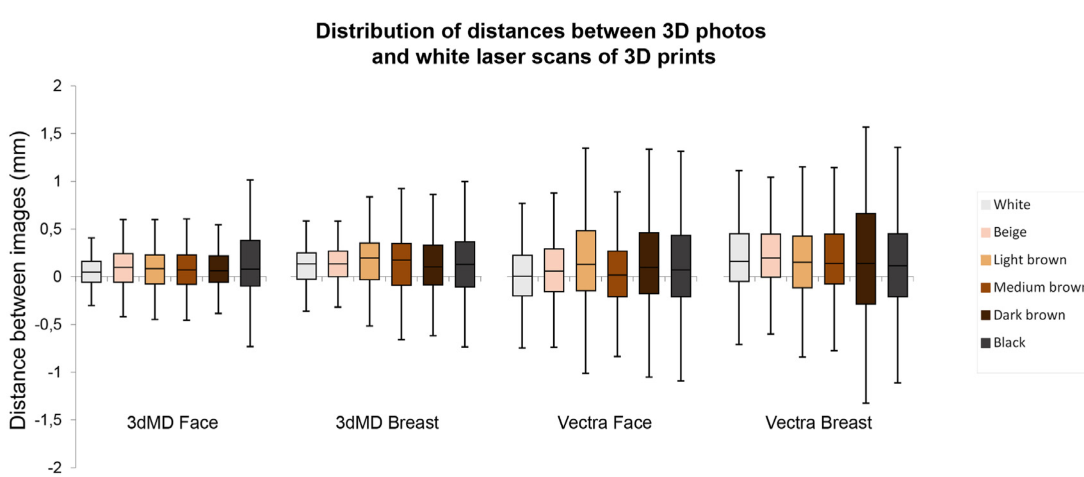

Figure 3 Boxplots of distances between 3D coordinates of 3D photos and white light scans of spray-painted 3D-printed breasts and face.

Figure 4 Skin tones of six of the seven subjects (one subject did not give consent to use her image in this publication).

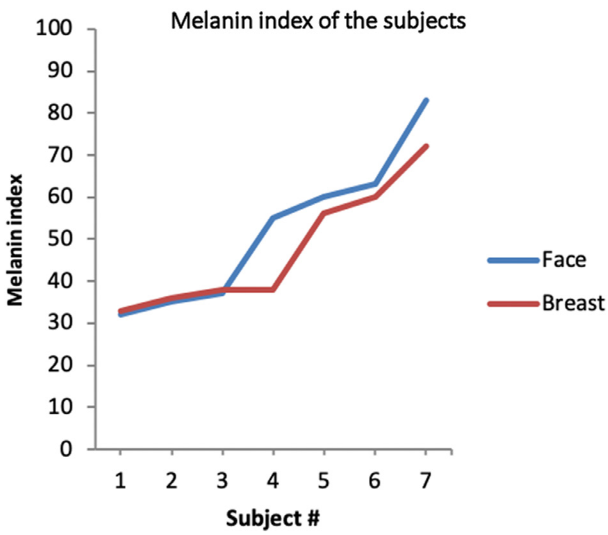

Figure 5 Melanin index of the subjects indicating the darkness of their skin. A darker skin translates to a higher melanin index.

six of the seven subjects are depicted in the figure. Figure 5 displays the melanin index of the subjects. The melanin index of the subjects' faces and breasts ranged from 32 to 83 and 33 to 72, respectively.

Figure 6 shows the color maps that correlate with the distances between the VECTRA-XT and 3dMD photos of the subjects' faces. The green color indicates that the VECTRA-XT image is in front of the 3dMD image, and the red color indicates that it is behind the 3dMD image. The color map scale ranges from -2.0 mm to $+2.0$ mm in 0.5 mm steps.

Overall, the 3D photos showed an accurate match. The distance between the 3D photos did not exceed 1.5 mm at any coordinate. Compared to 3dMD, the VECTRA-XT images seem to depict the faces slightly more elongated in the transverse plane, which makes the anterior region of the face more pronounced and the cheeks less pronounced.

For the breast images, a similar accuracy between the matches and patterns was found. The medial parts of the breast in the VECTRA-XT image were slightly in front of the 3dMD image, while for the lateral parts of the breasts, the VECTRA-XT image was slightly behind the 3dMD image. Because the breasts were nonptotic owing to the firmness or size of the breasts, the distance maps of the breasts showed no large deviations caused by potential line of sight errors in the inframammary fold or lateral breast. The breast images are not shown to protect the privacy of the subjects.

In Figure 7, boxplot of the distances between the 3D coordinates of the VECTRA-XT and 3dMD photos is shown for each subject. None of the 3D photos showed a clinically relevant mean deviation ($<$1.0 mm). For all skin tones, the distance between the images did not exceed 1.5 mm at any 3D coordinate. No correlation was found between the melanin index of the skin and the absolute means (Pearson's $R=-0.12$, $p=0.69$) or standard deviations of the distances (Pearson's $R=-0.06$; $p=0.85$). Furthermore, no difference between the standard deviations of the breast and face images was found (0.03 ± 0.10 mm; $p=0.40$).

Discussion

The goal of this study was to investigate whether the skin tone has a clinically relevant effect on the accuracy of 3D photos acquired with a hybrid or passive 3D stereophotogrammetry. Both systems did not show clinically relevant mean inaccuracies of their 3D photos from subjects and objects with a darker skin tone or paint color. A small positive correlation was found between the standard deviation of the inaccuracies of VECTRA-XT images and the melanin index of the objects. However, this correlation was not clinically significant due to its sub-millimeter size. The 3dMD and VECTRA-XT images showed similar mean accuracies as those of the gold standard. However, the accuracy of the 3dMD images had a smaller standard deviation.

To our knowledge, the effect of skin tone or object color on the accuracy of 3D photos was never investigated for either hybrid or passive stereophotogrammetry. Because the use of 3D photography in a clinical setting is increasing, validation studies on this subject are mandatory, particularly for the current passive 3D stereophotogrammetry-based VECTRA-XT system, as no publication on its clinical validation is yet available.

Passive stereophotogrammetry relies on the ability to detect details on the images of the subject, such as wrinkles and moles, which requires high-resolution images and adequate lighting conditions.[9] Active stereophotogrammetry relies on the distortion of the structured light pattern by the actual shape of the object. This makes it more robust to ambient lighting differences and slightly more favorable than passive stereophotogrammetry to acquire accurate images. However, the structured light pattern used by active stereophotogrammetry might not be projected adequately in certain anatomical regions such as the paranasal area and the submandibular regions.[23] Nevertheless, when appreciating the distance maps in our study, it seems that these areas show an equal error as other facial areas.

After surface-based registration, Maal et al.[7] found a mean reproducibility error of 0.40 ± 0.52 and 0.53 ± 0.62 mm for 3dMD photos. These results approximate the mean and standard deviations of the distances between the 3dMD and VECTRA-XT 3D photos of the subjects in this study. This suggests that the accuracies of both systems are similar.

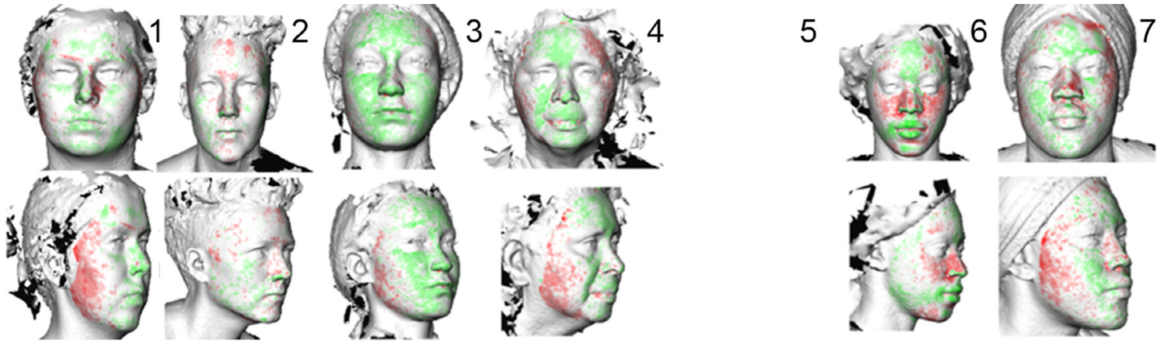

Figure 6 Matched VECTRA-XT and 3dMD images of the subjects' faces. The color map ranges from [−2 mm; +2 mm] with 0.5 mm steps. The green and red colors represent the relative positive and negative positions of the VECTRA-XT image compared to the 3dMD image. Because one subject did not give consent to use her image in a publication, only six of the seven subjects are shown.

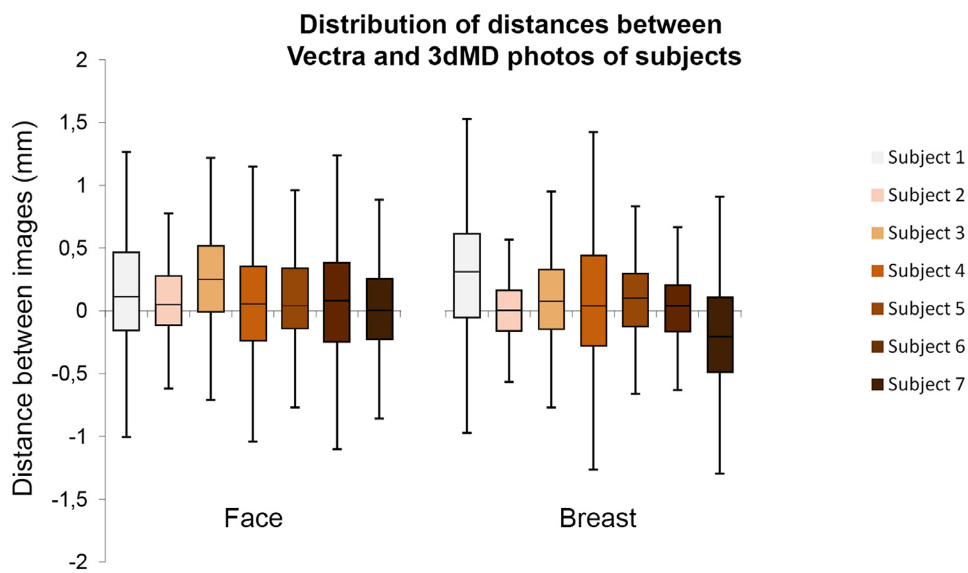

Figure 7 Box plots of the distances between the VECTRA-XT and 3dMD images of the faces and breasts of the subjects.

By using a 3dMD system on a mannequin head, Lübbers et al.[11] found accuracy with a mean error of -0.01 ± 0.55 mm after manually and digitally measuring the distance between landmark stickers. This accuracy is worse than the one found in our study, which is probably caused by the manually performed measurements by Lübbers and colleagues. de Menezes et al.[15] conducted a study on the accuracy and reproducibility of the Canfield VECTRA-CR system on an object and human faces. They found an error of 0.02 ± 0.03 mm when measuring the distances on the image of a cubic box with a 10 mm grid. Furthermore, they found that the random errors were always smaller than 1 mm when comparing distances between landmarks on two separate images of the same face. The standard deviation on their measurements was smaller than that in our study because they measured the distance over the surface of an object rather than the three-dimensional inaccuracy of each coordinate of a 3D photo.

To use 3D photography in areas with different populations, the capturing of different skin tones should be accurate. The results in this study show that both hybrid and passive 3D stereophotogrammetry systems provide accurate images of patients with light and dark skin tones. Therefore, the systems could be used worldwide among various populations. This suggests that this is also true for dynamic 3D imaging (4D), which is based on passive stereophotogrammetry in leading literature and is increasingly being used to investigate motion patterns in 3D.[24-26] However, further research is needed to confirm this.

A small number of 3D coordinates did exceed the clinically relevant threshold of 1.0 mm. These were mainly produced by the VECTRA-XT. When capturing images of the 3D prints, the VECTRA-XT system regularly had difficulties to produce a good 3D photo. We hypothesize that VECTRA software uses algorithms that reconstruct the image well when capturing a subject but not when capturing an object with a nonhuman shape. This led to increased errors in the images of the 3D prints captured by the VECTRA-XT. Therefore, the differences in the images of the subjects are probably more representative concerning the accuracy of the VECTRA-XT system. Movement of the subjects in the milliseconds between the two captures could have led to seemingly extra inaccuracy between the systems, but this is probably negligible.

In conclusion, this study shows that both hybrid and passive 3D stereophotogrammetry systems produce accurate 3D photos of subjects with light or dark skin tones. Therefore, both types of systems can be used in clinics with various populations.

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Conflicts of interest

None declared.

Funding

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Ethical approval

The medical ethical committee of the Radboud University Medical Center approved this study under file number 2017-3612.

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