Using Mobile 3D Scanning Systems for Objective Evaluation of Form, Volume, and Symmetry in Plastic Surgery: Intraoperative Scanning and Lymphedema Assessment

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Abstract

Background:

There has been ongoing development in the field of three-dimensional (3-D) Surface Imaging such as laser scanner and digital photogrammetry in recent years. Manufacturers tend to make new 3-D cameras compact, light-weighted, mobile, and user-friendly, similar to the development on the smartphone market.
Although 3-D scans have been used for patient consultations and digital documentation in Plastic Surgery since the 1980ties, there has been no significant development lately regarding its use for objective assistance during surgery.

Patients, Material and Methods:

Our research team presents the use of different mobile scanning systems (Sense, iSense, Artec Eva) as a new intraoperative 3-D scanning method for plastic-surgical procedures. We present several cases of aesthetic breast shaping and breast reconstructions with implants and free tissue transfer, such as lipofilling and complete reconstructions with microsurgical free flaps. In the future, these might assist surgeons with the pre-, post-, and intraoperative 3-D analysis, choice of therapy, consultation, and documentation.
Furthermore, we want to present the same scanners for the accurate assessment of arm and leg lymphedema patients. The diagnosis of lymphedema in patients and especially the outcome after treatment has been described with various methods so far. But in terms of clinical practicability physicians still rely on classical tape measurement. We compare volume estimation between the results of our 3D scanners against tape measurement and water-displacement.

Results:

The 3-D scanners were successfully validated for their intraoperative application to several patients. An intraoperative, objective measurement of volume to evaluate form and symmetry was possible for aesthetic procedures, such as breast augmentation and reduction, as well as for breast reconstruction with lipofilling and free tissue transfer. 3D scanning was used for key steps in all these procedures with minimum delay of the procedures and instant feedback for the surgeons. There was nonetheless significant difference between the used 3-D scanners in terms of mesh quality and textures.
We could also validate all mobile scanners as objective tools to capture lymphedema in patients for documentation before and after treatment. The biggest difference was shown against tape measurement, which is highly dependent on correct placement and the different estimation methods.

Conclusion:

In this work, we share our first experience with the intraoperative use of new mobile 3-D camera systems, discuss pros and cons, and show selected patient examples. The newest mobile scanning systems showed highly accurate 3-D scans during surgery regarding the actual form, shape, volume shifts and differences.
Furthermore, mobile 3-D camera systems were able to accurately assess lymphedema especially for the leg and may become the future chosen method to evaluate different treatments of lymphedema.
Although the development of 3-D scanning devices rapidly increased, we still lack appropriate software development for medical usage. Newer software has to become more practicable, user-friendly, and especially versatile for different plastic surgical procedures.

Keywords:

3d body scanning, 7th international conference on 3D Body Scanning Technologies, Lugano, mobile scanning, intraoperative scanning, plastic surgery, 3D imaging, breast imaging, lymphedema

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1. Introduction

1.1 Current Literature

There has been ongoing development in the field of three-dimensional (3-D) Surface Imaging such as laser scanner and digital photogrammetry in recent years. With news about technical innovations on 3-D Imaging emerging monthly nowadays, their medical use is still limited to patient consultation and digital pre- and postoperative documentation in Plastic Surgery. Although research has been conducted since the 1980ties, there has been no significant development regarding its use for objective assistance during surgery.

3-D Surface Imaging offers an objective, non-invasive, and radiation-free diagnostic tool for the pre- and postoperative documentation of the human body. Current literature offers a variety of publications regarding 3-D surface imaging mainly from laser scanners or photogrammetry for medical purposes (1-3). Generally, laser scanning systems have been utilized especially in automobile industry for construction and quality control for decades. This knowledge has been transferred to the surgical field especially in Oral & Maxillofacial Surgery for the preoperative 3-D operation planning in combination with Computer Tomography (CT) imaging (4-6).

In recent years, digital photogrammetry - the 3-D surface reconstruction from photography - has evolved into several user-friendly commercial tools, which have been used for the documentation of surgical patients in manifold fields. Different stationary 3-D camera systems, such as the Vectra System® (Canfield Inc., USA), have been assessed and the current trend is focusing on the planning of reconstructive surgery and their follow-up documentation in outpatient clinics. These systems are offering a reliable evaluation of form, contour, symmetry, and texture of the body (2, 7-9). Currently manufacturers tend to make new 3-D cameras compact, light-weighted, mobile, and even more user-friendly, which shows similarity to the development on the smartphone market.

With this technique breaking away from their former solely stationary use, it opens new many and varied applications in Plastic and Reconstructive Surgery, which focuses on the reconstruction and improvement of disturbed form, surface, and function of the human body after trauma or tumors. Next to the restoration of form and function as two surgical indications, a major role in every reconstructive case is an aesthetical pleasing result. To measure such an outcome, there have been numerous objective and subjective two- and three-dimensional tools for the pre- and postoperative evaluation of form and aesthetics of the body introduced. Our research group focuses to advance the well-established use of 3-D Imaging for pure documentation onto different applications with new mobile devices.

1.2 3-D Surface Imaging in Plastic Surgery

In our department for Plastic Surgery, we use 3-D imaging for two major topics:

Our first aim is to evaluate the correction and reconstruction of major tissue trauma of the human trunk or extremities. One prime example is the challenging breast reconstruction with free tissue from the underbelly, called Deep Inferior Epigastric Perforator (DIEP) flap following a complete breast resection (**see figure 1**) (10-12).

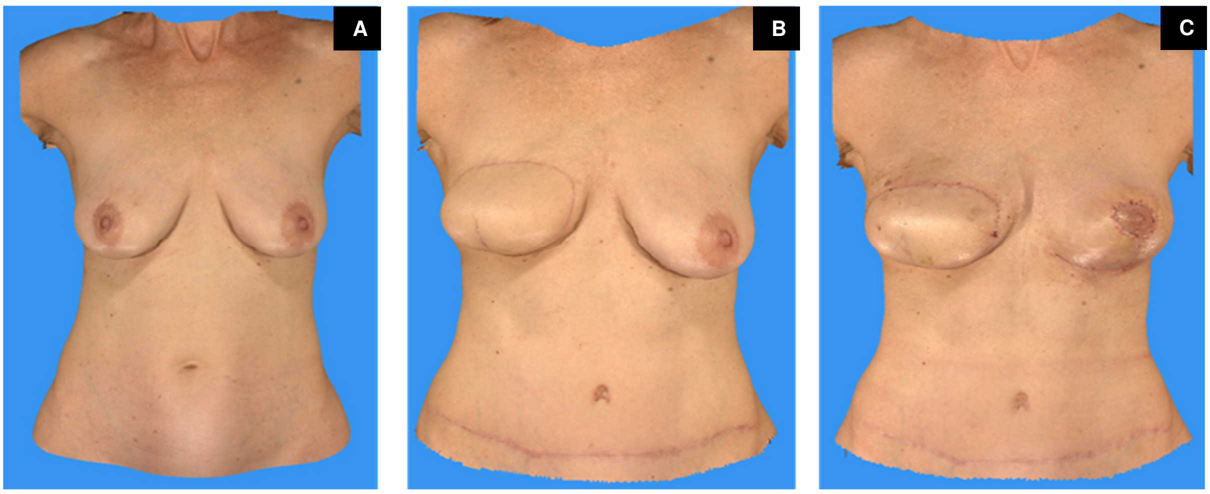

***Figure 1**: 3-D Vectra Scan of a female 45-year-old right-sided breast cancer patient in our outpatient clinic. The right breast was completely resected and in a single-stage operation immediately reconstructed with DIEP-flap. (A) Preoperative scan, (B) 3 months after surgery, (C) and 2 weeks after contralateral breast symmetry correction and lipofilling of the DIEP-flap.*

Besides requiring a lot of experience and skill to perform such an operation, it is necessary to plan a free tissue transfer in detail (12), taking many factors such as the receiving site, former breast volume and surface, as well as an estimated overcorrection of the operated site compared to the healthy breast into consideration (13).
In Reconstructive Breast Surgery, there are several key steps in the intraoperative decisions about how to shape form, symmetry, and volume of the reconstructed breast compared to the opposite site. These decisions are made based mainly on the objective tape measurement, weighting or water-displacement measurement of specimens, and the subjective experience of the surgeon. The patient is viewed and measured in a lying and sitting posture, which allows a surgeon to envision a outcome based on gravity and skin laxity better.
The decisive factor is that these objective parameters are shaped and altered during surgery based on the surgeon's experience. So far, there has been no research published about the use of 3-D imaging during surgery, as most 3-D Imaging devices are stationary or not mobile and thus impracticable of acquiring 3-D scans in an operation room (14, 15).
From the facts, we see a high potential of intraoperative 3-D Imaging assisting surgeons during Plastic and Reconstructive Surgery with objective parameters and a reliable decision making (2, 16).
Secondly, we aim to use those new mobile 3-D cameras to evaluate parts of the body which have been left out in recent years or have been hard to capture (3) such as the upper and lower extremity of patients. These areas are for former 3-D systems, which could not cover 360 degree angles and therefore would have to fill a room consisting of cameras, in several ways difficult to acquire: they had to cover different aspects of very delicate structures from unnatural views for most 3-D imaging systems. With the new hand-held scanners emerging since 2012, these obstacles were mastered step-by-step and current 3-D mobile systems can meet these requirements satisfactorily.

2. Patients, Material and Methods

Our research team presents the use of different mobile scanning systems (Sense, iSense, Artec Eva) as a new mobile 3-D scanning method for plastic-surgical procedures. These systems are using different kind of sensor techniques with the Sense and iSense relying on infrared depth-sensors and the Artec Eva using the manufacturer's "structured light" technique. The three scanners are hand-held, with the iSense connected directly to an iPad Air (Apple Inc., Cuppertino) and the other two connected to a remote laptop via cable. The Artec Eva is in addition powered by a battery pack.
So far, there has been no intraoperative 3D imaging system available to gather and visualize objective data such as form, volumes and symmetry to further assist surgeons during procedures. For intraoperative scanning, all devices had to be moved in a pattern from left to right under sterile conditions until all aspects of the patient's body have been covered by the sensors (see **figure 2**) of a scanning process with the sense scanner and results). Scans were directly processed during surgery and could be viewed and evaluated while the surgeons proceeded with their operation.
We present several cases of intraoperative aesthetic breast shaping and breast reconstructions with implants and free tissue transfer, such as lipofilling and complete reconstructions with microsurgical free flaps. In the future, these might assist surgeons with the pre-, post-, and intraoperative 3-D analysis, choice of therapy, consultation, and documentation.
Furthermore, we want to present the same scanners for the accurate assessment of the lower extremity (see **figure 3**) for later use on lymphedema patients. The diagnosis of lymphedema in patients and especially the outcome after treatment has been described with various methods so far. But in terms of clinical practicability physicians still rely on classical tape measurement. We compare volume estimation between the results of our 3D scanners against tape measurement and water-displacement.

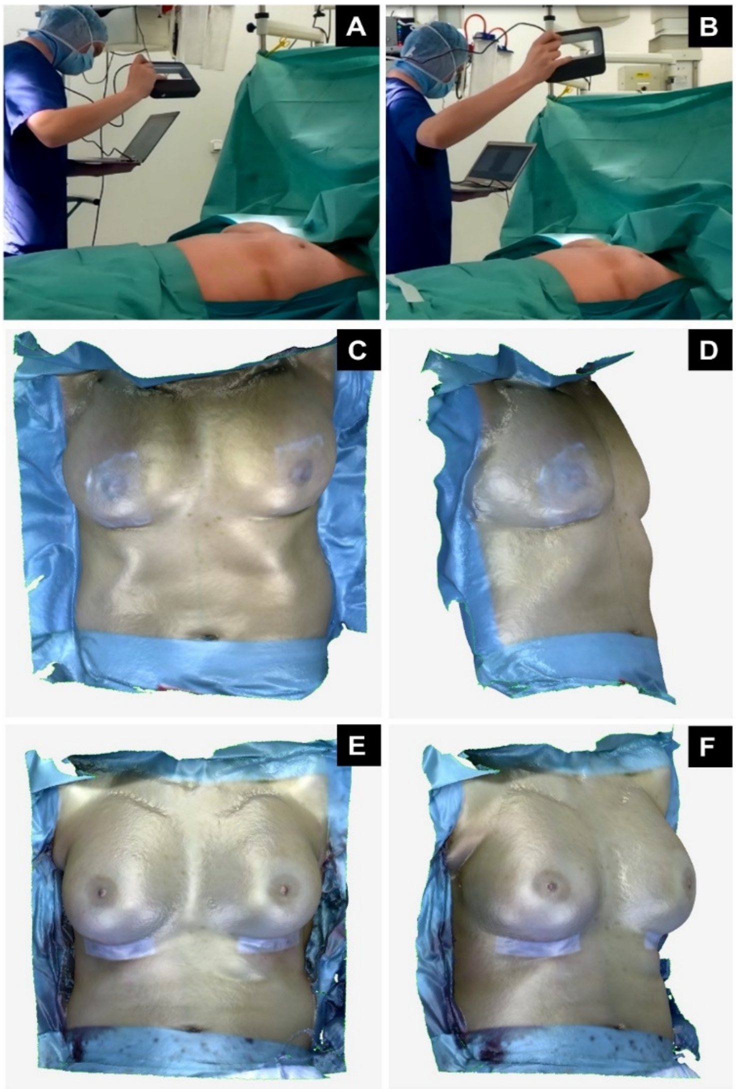

Figure 2: *Intraoperative scanning with the Sense 3D Scanner (A,B) of a 46-year-old patient for bilateral breast augmentation. (C,D) showing the scans before surgery on the operation table and (E,F) the final result after implants have been inserted and wound closure.*

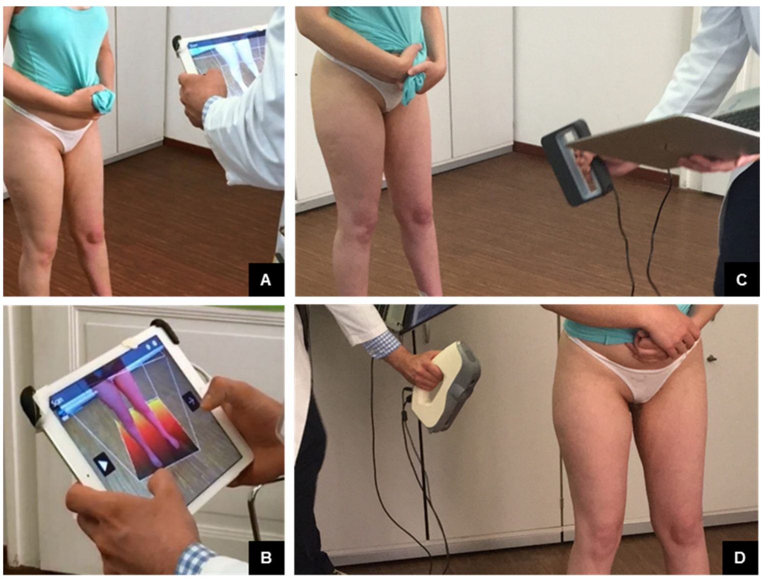

Figure 3: *Preliminary pictures of the scanning process of the lower extremity in a female 34-year-old lymphedema patient with the iSense (A, B), Sense (C), and Artec Eva (D) without using a turntable.*

3. Results

3.1 Intraoperative Scanning

Results from our preliminary study (17) showed that 3-D imaging with the Artec Eva yielded best results regarding accuracy in shape acquisition and volume determination compared to our established Vectra 3D Surface Imaging System for patients in upright standing position. Even delicate areas such as the inframammary fold could be captured easily and was reconstructed properly, except for very obese patients with either gigantomasty or a higher Body-Mass-Index than 27 kg/m².
The sense scanner on the other hand was acceptable for lean patients with small to medium sized breasts. Nonetheless, neither the inframammary fold nor the texture quality showed promising for further research with the Sense Scanner.
We like to present two short cases of 3-D scanning in the operation room from our 50-case series to highlight the possibilities and limitations of both the Sense 3D Scanner and Artec EVA:

3.1.1 Case 1 – 18 year old patient with tubular asymmetric breasts

Tubular asymmetric breasts are especially for young women a significant social isolating factor in the development of healthy self-esteem. Many women seek surgical correction with breast augmentation or different approaches. In this case, we want to show the limitations of the Sense 3D Scanner for complex deformities of the chest such as tubular asymmetry.

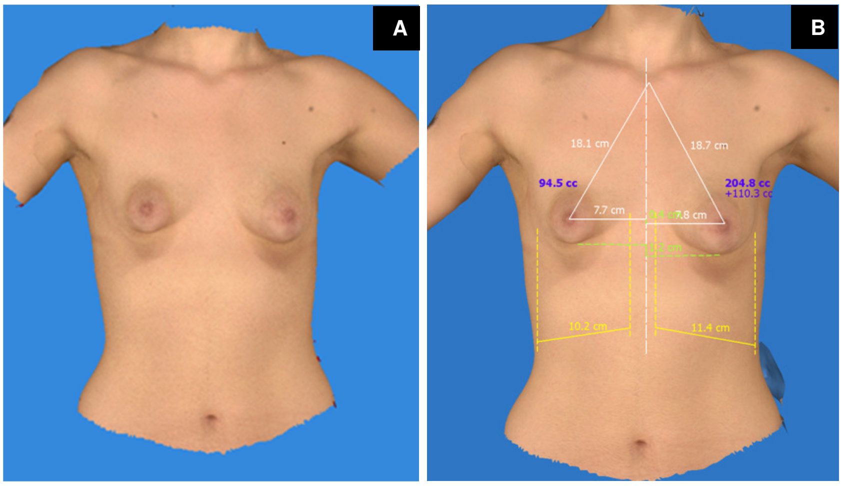

***Figure 4**: Preoperative Vectra 3-D scan of an 18-year-old patient with tubular asymmetry in our outpatient clinic. The patient was scheduled for breast lift with silicone implant augmentation. (A) shows the frontal view of the patient and according digital assessment on (B).*

In comparison to our Vectra system (see **figure 4**), the Sense scans are not capable of acquiring difficult to capture regions such as the inframammary fold (see **figure 5**). The displayed holes had to be digitally repaired with the accompanied software solution, resulting in more erroneous volume calculations. For the postoperative 3-D scan (see **figure 6**), the Sense scanner produced flawless mesh quality with the now more simple and round breast surface. Furthermore, texture quality is poor and hinders digital landmark placement, as well as the digital measurement of classical breast measurement.

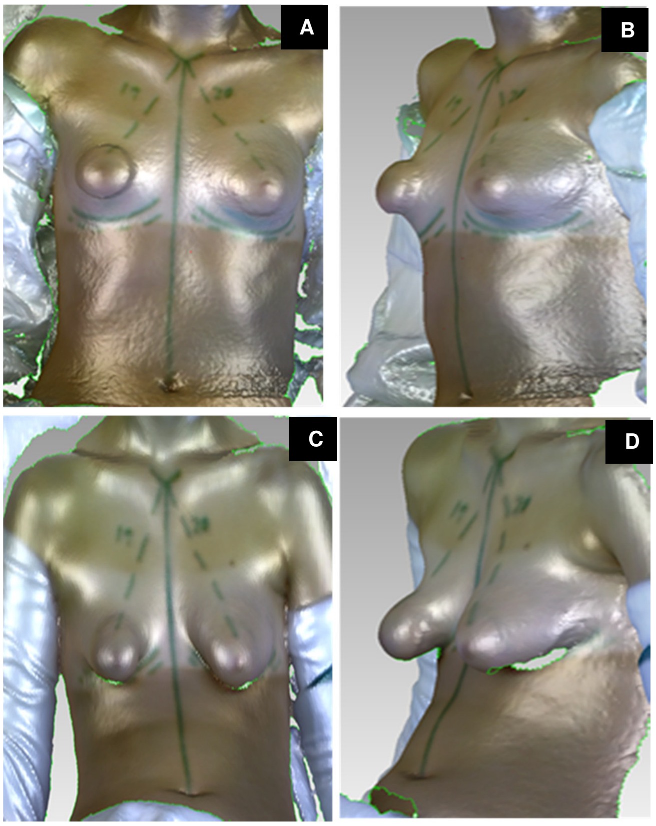

Figure 5*: Intraoperative 3-D scan with preoperative markings of the 18-year-old patient in a supine (A, C) and sitting (B, D) position. Scans were conducted at the start of the procedure with consecutive assessment on major key-points of surgery. Scans were not altered or processed further to highlight the problematic capture of the inframammary fold in the sitting posture (B, D). Texture quality is not essential for volume change assessment but not satisfactory in general.*

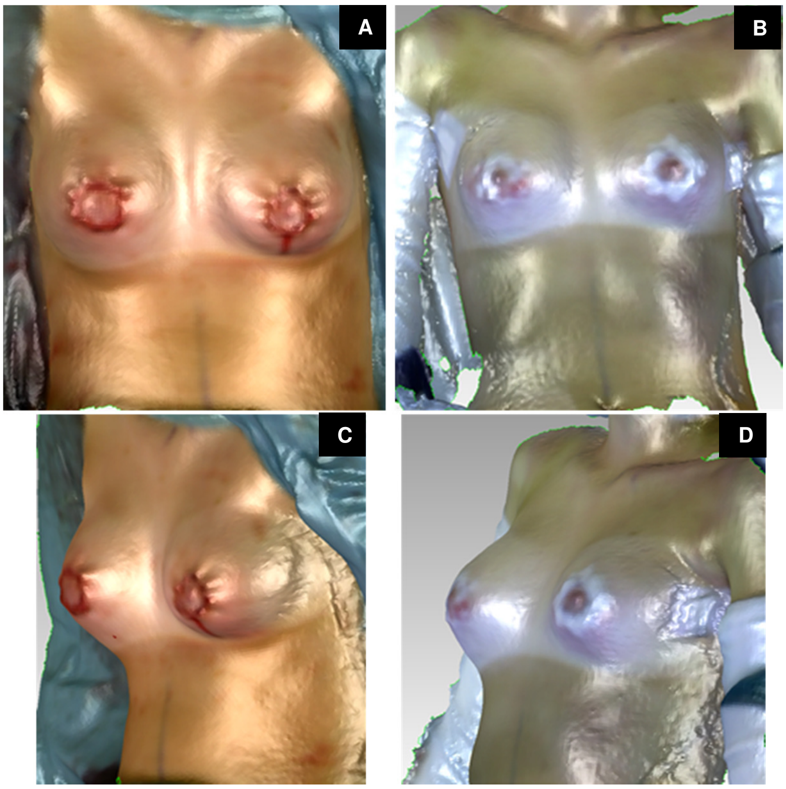

Figure 6*: Intraoperative 3-D scan after the bilateral mastopexy and implant insertion in a supine (A, C) and sitting (B, D) position. We showcase direct lighting with our operation light in (A) and (C). The same for (B, D) without it.*

3.1.2 Case 2 – 34-year -old patient with left-sided breast cancer and breast reconstruction

A 34-year-old patient was referred by our gynecologists after recurring breast cancer and complete resection of the left breast regarding breast reconstruction (see **picture 7**). There were no signs of second recurrence after thorough diagnosis. After several consultations, we scheduled surgery together with the patient wishes for a breast reconstruction with a pedicelled Fleur-de-Lis-Latissimus-Dorsi muscle flap and breast implant. The correct size of implant had to be determined during surgery but was estimated between 125 – 450 mL of volume.

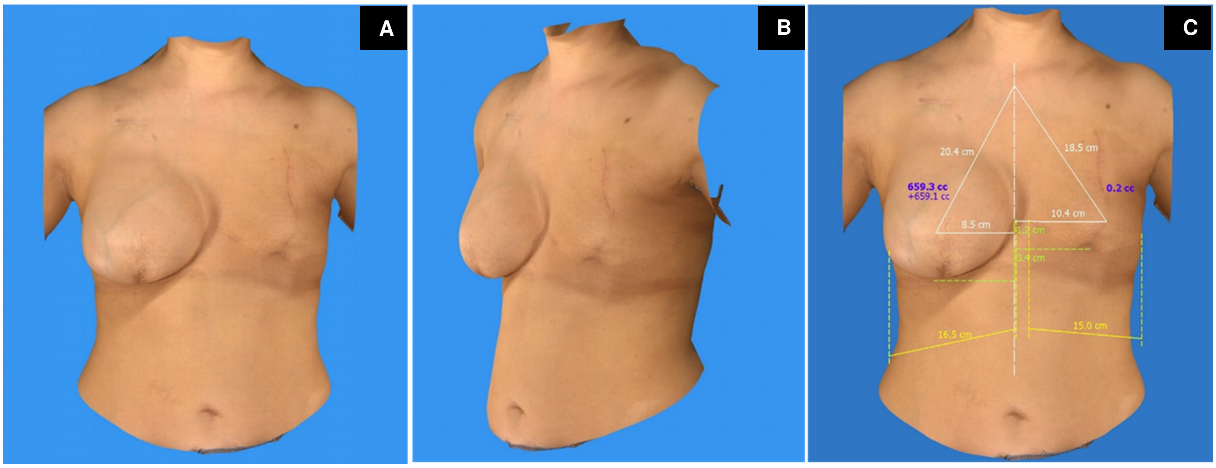

***Figure 7**: Preoperative Vectra 3-D scan a 34-year-old breast cancer patient after left sided ablation in frontal view (A), left lateral view (B) and with breast symmetry calculation (C) showing a difference of approximated 659 mL.*

During surgery, we performed 3-D scans with the Artec Eva at major key points to assess breast symmetry and volume change. We present the following states: after pedicelled muscle flap insertion (**figure 8**), following the direct implantation of different breast implant sizers to achieve breast symmetry (**figure 9**).

As **figures 7-9** showed, 3-D Imaging is a valuable tool to assist surgeons during complex reconstructive procedures with multiple different steps of achieving an aesthetical pleasing result. For this manuscript, we were not able to show every 3-D scan of the different sizers used. Following the end of the operation, the flap was at all time vital and the patient was very satisfied with the final result after 6 months.

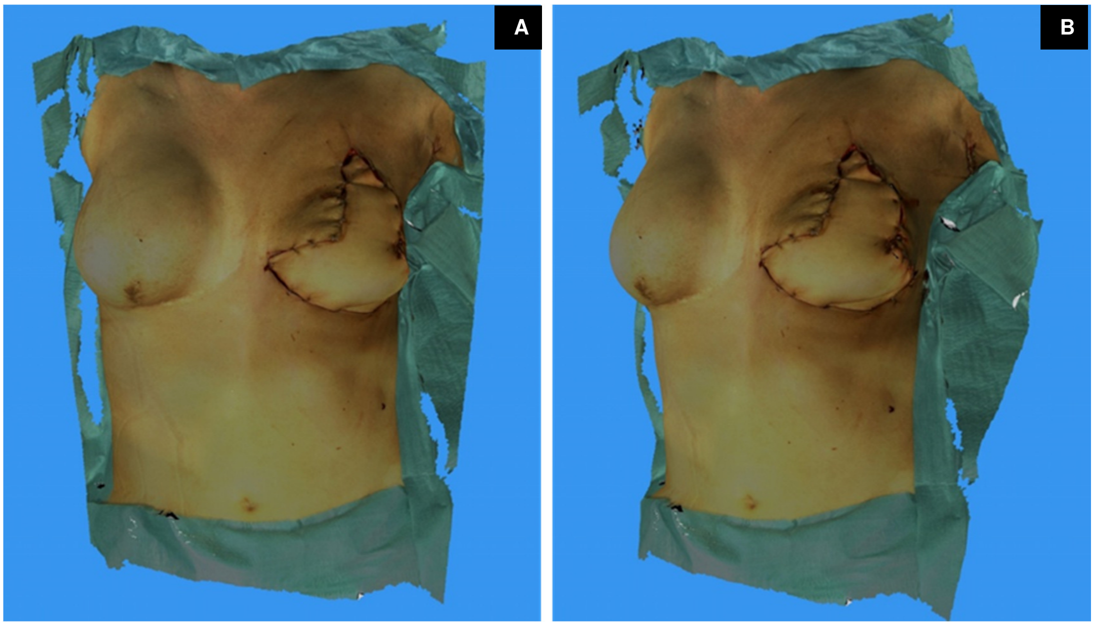

***Figure 8**: Intraoperative Artec Eva scan after performing pedicelled latissimus dorsi muscle flap and ventral transposition. The frontal (A) and left lateral (B) view in a sitting posture showed both subjectively and objectively (350 mL) significant volume and surface asymmetry at this stage of the operation.*

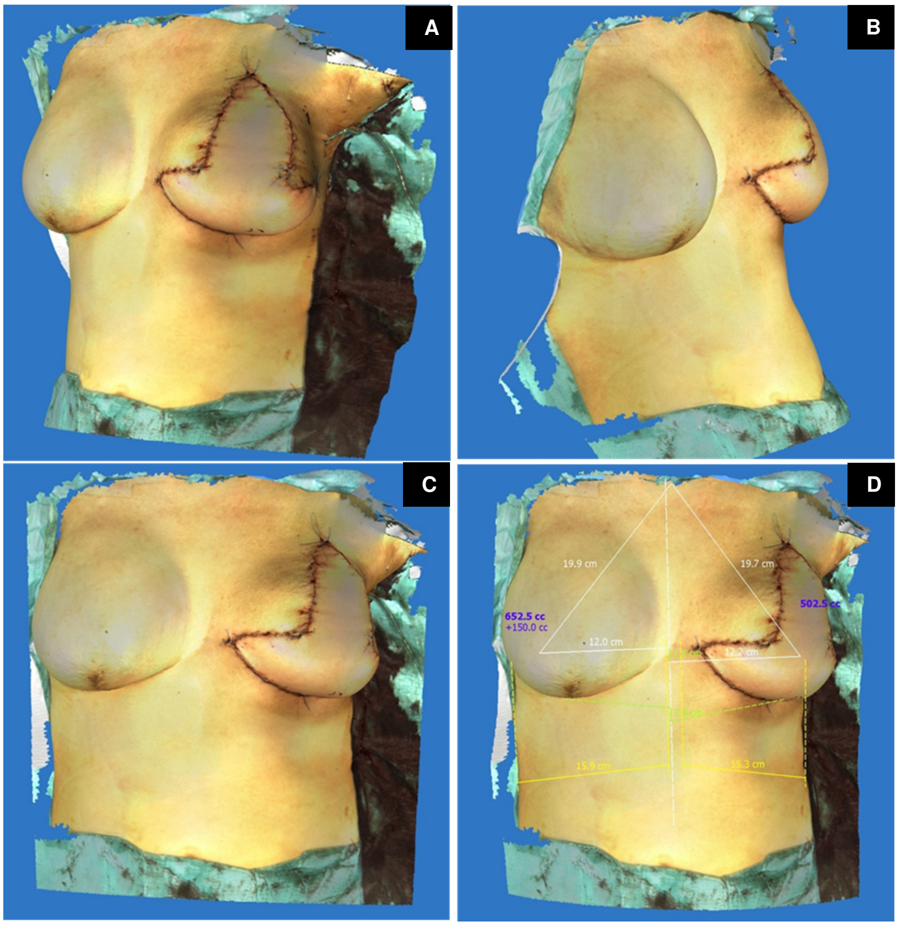

Figure 9*: Intraoperative scan after additional implantation of a 225 mL implant. Lateral left (A), lateral right (B) and frontal (C) showed an aesthetical pleasing result. 3-D volumetric evaluation (D) revealed a 150 mL.. Besides the good result, this difference could not be compensated by a bigger implant volume due to venous stasis of the flap.*

3.2 Lymphedema assessment

3-D Scanning of the lower extremity showed a high correlation (R > 0.92) to the water-displacement reference with a mean deviation of 2.0 ± 1.0% and maximum deviation of 5.6%. All measurements were observer-independent (Variance Coefficient 0.4 ± 2.3 %; ICC > 0.96). See **figure 10** for a comparison of all three scanners on a female patient.

Separating the lower extremity into its anatomical parts, the feet region showed highest mean deviations (10.2% ± 3.1% SD) especially for the Sense 3D Scanner.

Compared to manual tape-measurement we found significant differences (9.4 ± 4.5%; p < 0.001) for all 3-D volumetric tools with up to 1500 mL, although tape-measurement resulted in every case into higher volume estimations.

Considering the time for volume assessment, 3-D scanning allowed in general 3-times faster results (28.7 ± 3.1 s) than the manually placed tape measuring.

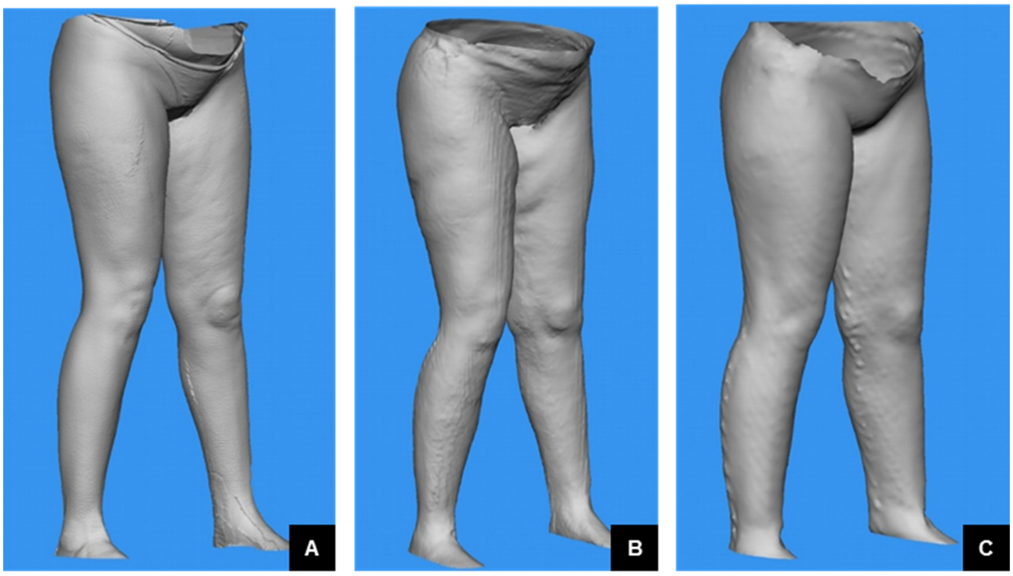

Figure 10: *3-D mesh without textures of a 34-year-old female patient with Artec Eva (A), Sense (B), and iSense (C). All devices produced sufficient dense meshes for volume quantification. Limitations between all three 3-D scanners are seen especially between the high-quality model (A) and the low-priced (B) and (C).*

4. Discussion

With this manuscript, we wanted to highlight the great potential of 3-D Imaging with newer mobile and hand-held scanning devices for new approaches in Plastic Surgery.

3-D capture was user-friendly and swift with each of the tested scanner. Surgery was prolonged by a 20 – 60 seconds per scan and widely accepted by all operating surgeons. Furthermore, the visualisation and quantification of essential parameters during surgery can assist surgeons next their profound subjective experience with objective values.

With our 3-D Imaging protocol for patient positioning and draping before and during scanning, we could standardize the 3-D capture process in different positions, which may greatly influence the value of measured parameters(18). The upright position is essential to assess the outcome at the end of procedures with the later result on patients after several weeks and months. Failing to achieve standardized positioning may lead to false parameters or producing errors in the 3-D capture. Therefore, further studies with a high count of patients and in comparing to the subjective rating of surgeons have to be conducted before intraoperative 3-D Imaging becomes a reliable standard for Plastic Surgery.

With the intraoperative assistance of 3-D surface scans, surgeons will be able to combine the intraoperative results with preoperative 3-D-CT-Angiography and receive more reliable results. Due to skin laxity and gravity following surgery, the resulting changes over time to the immediate postoperative outcome can be objectively quantified with the new 3-D devices and may help in estimating the volume loss in procedures such as lipofilling and flap reconstructions to precisely overcorrect the volume during surgery and achieve a symmetrical and reliable result after 6 months. Finite-Element-Analysis studies already showed how to predict tissue changes of the breast for the planning of breast-shaping procedures (10).

Especially for our lower extremity scans, the volume quantification will add valuable objective parameters to the controversial discussion about which treatment is sufficient for lymphedema patients. Most of the published studies about lymphedema surgery or conservative treatment focus on quality-of-life aspects with preoperative and follow-up 2-D images. Although quality-of-life is of highest importance, 3-D Imaging allows to evaluate changes between healthy and pathological body parts, can calculate volumetric and shape changes precisely, and thus can play a major role in deciding which treatment is sufficiently reducing swelling. The manual tape measurement is next to water-displacement the gold standard and these two methods are the only valued in current guidelines for lymphology for the evaluation of treatment outcome. With our and other new study results, 3-D Imaging may become a crucial part in these guidelines in the future. We are currently improving our extremity scans with a self-build turntable to reduce scanning time and make the scanning process even more user-friendly.

Furthermore, with new scanner being introduced per year(14, 17), new 3-D scanning systems will add to the current possibilities of plastic-aesthetic and plastic-reconstructive procedures in terms of standardisation and evaluation. Current 3-D scanner prices are gradually falling and may lead to a wider acceptance in clinical practice outside the research-driven application. On the other hand, current 3-D evaluation software is only slowly progressing and developing with few providers on the market. Next to the follow-up documentation of surgery for limited body parts and aesthetic consultation with simulations based on plain morphing, the used software and alternative ones are still lacking a wider approach especially for the applications we presented with this manuscript (2, 3, 19).
Although laser scanner produce highest precision for 3-D scanning (8, 20, 21), they are in comparison more expensive, not as adaptable as the new mobile and hand-held scanner systems, and especially less accepted by patients. For all current mobile hand-held scanner, the major limitation lies in involuntary movement of the patient: we can reduce this intraoperatively with close communication with the anaesthetic, but for 3-D capturing of limbs the patient must hold the position to reduce mesh artefacts.
The provided pictures are showcasing the difference between professional systems with a homogeny illuminated surface and high-quality textures by the Artec Eva and the low-quality textures and very light-dependent scan by the Sense scanners (see **figure 6**). Although the texture is not essential for initial mesh design and volume calculation, it is important for distance calculations such as classical breast measurements and surface alignment.
Comparing mesh quality, the low-priced sense scanner is capable to capture simple surfaces the best as seen in the aesthetic breast augmentation in **figure 2**. With rising complexity of the surface, such as the breast reconstruction or tubulary breasts (see **figure 5, 6**), 3-D capturing with the Sense scanner failed to acquire important regions like the inframammary fold and are therefore very limited in these cases. The Artec Eva can capture these details even better than our Vectra System and is currently used for all our form-shaping procedures during surgery.
Every new scanning device must fulfil besides the manufacturer's details about high accuracy and detail the criteria mentioned above, before further research should be conducted and objective data is given to the operating surgeon or consulting physician.

5. Conclusion

Our research group validated new hand-held 3-D scanning systems for the objective assessment during plastic-surgical procedures and for full 360 degree capture of the lower extremity successfully.
With the presented cases and data, we could show a reproducible and accurate method to assess different breast shaping procedures such as breast reconstructions in terms of volume and surface analysis. Furthermore, we could quantify leg volumes against water-displacement and tape measurement with minor deviations in comparison to the gold standard. Both approaches of 3-D scanning showed quality differences between professional and consumer systems. With the rapid development in this sector, more companies will invest into and invent new 3-D imaging systems thus lowering the mean acquisition costs. These systems may play a major role in the evidence-based documentation and evaluation of pre-, intra-, and postoperative surgical states of a patient, which will influence the patient consultation and therapy options of common surgical indications in the future.
Nonetheless, current 3-D camera systems lack automatization of scan processing and evaluation for our approach. To achieve this, newly developed high-resolution 3D cameras and special software is needed. Further progress in custom-made intraoperative scanning systems must be approached, but we see an utmost high potential in 3-D scanning to assist surgeons during their decision making with objective and reliable parameters.

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