Structured light scanning to evaluate three-dimensional anthropometry in HIV facial lipoatrophy

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Abstract

The psychological and social impact of the lipodystrophy syndrome on HIV-infected individuals may be quite considerable and adversely affect their quality of life. Currently no validated assessment tool for facial lipoatrophy is available. The main objective of this paper is to evaluate the reliability of interactive anthropometric landmark localization based on digitized 3D facial images. By comparing both computed tomography (CT) and structured light scanning we try to demonstrate that surface scanning shows a higher sensitivity in measuring facial reference points. Besides, we evaluate the reproducibility of facial 3D white-light scans. Three HIV-positive men attending our plastic surgery outpatient clinic for treatment of facial lipodystrophy were enrolled in the study. Localization of anthropometric landmarks measurements was performed on the patients. All patients underwent a facial CT and a facial white-light scanning on the same day. The inter-landmark distances measured on facial models developed from CT aided with *VirSSPA* 3D software and structured light scanning were compared to the real human models. We found that facial distances measured in the CT 3D reconstruction showed a mean error margin of 0.357 cm from the real distances measured on patients. On the contrary, mean error margin with the white-light scanning was of 0.096 cm. In both cases, measurements were found to be statistically significant ($P<0.05$). When compared to CT reconstructions, white-light surface scanning offers a more accurate landmark localization as well as reliable reconstructions of up to less than the tenth of a millimetre as average when compared to real measurements on facial human models.

Introduction

The introduction of antiretroviral therapy (ART) has dramatically reduced the mortality and incidence of opportunistic infections among human immunodeficiency virus (HIV)-infected patients.[1] Usually the disease is well-controlled and those affected quite often develop healthy and productive lives. However, in many cases their facial appearance suggests the opposite and frequently serves as a stigma and psychological burden.

Recently, it has been recognized that ART is associated with a process involving body shape changes known as lipodystrophy or, more recently, fat redistribution syndrome. The resulting condition is characterized by loss and/or redistribution of fat, insulin resistance, and proatherogenic hyperlipidemia. This is a feature different from HIV wasting syndrome, which is predominantly due to loss of muscle mass. Some investigators suggest the existence of a link between HIV lipodystrophy and the introduction of HIV protease inhibitors on the basis that both facts were reported in parallel from 1997 onwards.[2,3] The encouraging clinical, virological, and immunological effects of protease inhibitors may have favoured certain tolerance to potential side effects. In fact, a growing body of evidence shows that lipodystrophy has a prevalence of up to 83% and causes noticeable disfigurement in ART-treated HIV patients.[2-4]

These patients characteristically show increased fat around the abdomen, dorsocervical fat pad enlargement (buffalo hump), and sometimes breast hypertrophy.[3-5] Fat is mainly lost from the limbs, buttocks, and face, especially from the nasolabial regions, the temples and, when the syndrome is present in severe form, the eye sockets.[5] This disfigurement can lead to significant psychosocial stress, resulting in decreased treatment compliance. Once lipoatrophy has appeared, no systemic therapy will apparently reverse the fat loss to an appreciable extent. The most effective treatment is soft tissue augmentation.

The contours of the face are extremely complex and rather variable among individuals. Monitoring subtle volume changes over long time periods in an ageing population is particularly difficult and a cheap, non-invasive technique is needed to measure body habitus changes, including those related to the face.

Three-dimensional (3D) surface digitization offers tremendous opportunities in the clinical documentation and for objective analysis of the human face. Measurements and characterization of facial surface anatomy are fundamental clues to the objective analysis of facial deformity. Subtle changes of HIV-associated facial lipoatrophy have been measured through the years by clinical examination, facial anthropometry and radiological tests such as computed tomography (CT).[6-8] However, current innovations in surface scanning technology provide a potentially useful technique for a more accurate 3D documentation of the face.[9]

We have recently developed *VirSSPA* software that can be used to provide a detailed 3D facial image reconstruction in conjunction with CT[10] and white-light scanning. The aim of this study is to evaluate the reliability of interactive anthropometric landmark localization based on digitized 3D facial images. By comparing both CT and white-light scanning we try to demonstrate that white-light surface scanning shows a higher sensitivity in measuring facial reference points. Therefore, we analyze the role of this application in the preoperative evaluation of HIV-associated facial lipoatrophy. We also discuss the apparent benefits of the new tool and identify sources of error associated with the technique.

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Materials and Methods

Patient selection

Three HIV-positive men attending our plastic surgery outpatient clinic for treatment of facial lipodystrophy were enrolled in the study. All patients gave informed signed consent to participate and were required to be aged 18 years or older and HIV antibody positive. Institutional review board approval was also obtained for this study.

All investigations and procedures were carried out over a month period at the same institution and by the same primary and assisting surgeons. All patients underwent a facial CT

and a facial white-light scanning on the same day. The radiological techniques were performed by the same radiology team. No patients were excluded under exclusion criteria comprising active opportunistic infection, malignancy within the previous 3 months or previous HIV wasting syndrome.

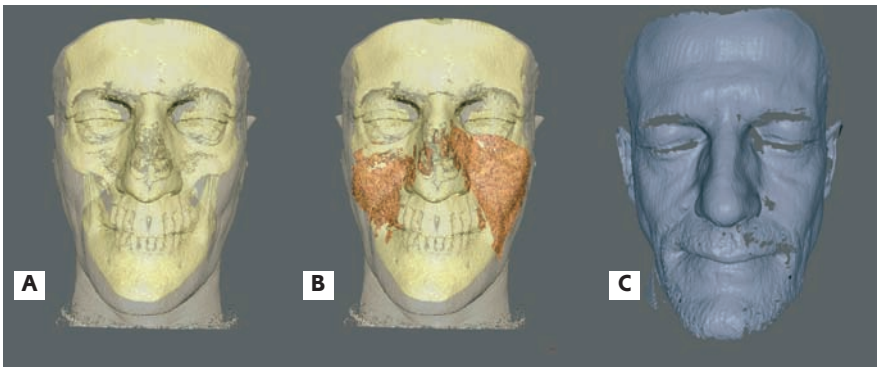
Image acquisition and reconstruction

Patients underwent imaging in the supine way to mimic the intraoperative position and the scans were performed in a standardized way by the same technician. Each individual was requested to adopt a neutral facial expression, with the head supported by a head-rest.

A General Electric LightSpeed 16 multidetector row CT scanner (General Electric Company, Fairfield, CT, USA) was used. The acquired volumetric data was then used to reconstruct images with a slice width of 0.63 mm and a reconstruction interval of 0.8 mm. The resulting complete set of reconstructed images was automatically transferred to a computer workstation, which generated the reformatted images in multiple planes (coronal, axial, sagittal and oblique) and in three-dimensional volume rendered images (Figures 1A and 1B). This system allowed to take measurements so that different planes of space could be automatically correlated. All data were stored as a DICOM-compatible (Digital Imaging and Communications in Medicine) file onto a CD-ROM to be loaded into a personal computer.

3D surface data were acquired using a commercially available white-light scanning device (SidioPro model, NUB3D S.L. Barcelona, Spain), with an optic of 1.4 Mpixels and an acquisition time of 1.5 seconds. The digitalization system used was 3D SidioPro Advanced. Images were then loaded as a .obj file onto the *VirSSPA* software (see below) and all subsequent anthropometric analyses were performed interactively on the computer monitor (Figure 1C).

Based on those CT and surface scanning images we performed a 3D reconstruction of the face and facial structures. Each image was traced using computer software to outline the structures of interest. Individual structures were drawn and given structure-specific colour codes at each axial level. The models were thereafter incorporated into the virtual reality environment using an original set of the modular software programming tools called *VirSSPA*, developed in our hospital by a multidisciplinary team composed by specialists in simulation and virtual reality applications development and by medical doctors.[10] The models were programmed to run on a personal computer and be displayed on a high-resolution monitor (Figure 2).



Figures 1. Different facial reconstructions in patient number 2. A) *VirSSPA* 3D reconstruction of the facial contour from the CT DICOM archives, the underlying osseous structure can be clearly seen throught the facial skin by transparency; B) cheek fat tissue is represented in orange. A potential atraction of our approach is that measurements of the facial fat loss volumes, which directly affect facial contour, could be performed; C) facial surface reconstruction acquired using a white-light scanning device.

Interactive localization of anthropometric landmarks measurements

Measurements on the patients were obtained as described by Hillesund *et al.*[11] Similarly, the scanning measurements and CT images were taken with the teeth in occlusion and the lips in a relaxed position.

Inter-landmark distances were recorded to the nearest tenth of a millimetre at each visit using a vernier caliper. The cephalometric measurements for the soft tissues points were calculated as in previous studies by Johannsdottir *et al.*[12] Figure 3 shows the soft tissue cephalometric points recorded.

VirSSPA software program allows accurate placement of landmarks using horizontal and vertical guidelines which aid in the location of the 3D landmarks. The landmarks are identified and the computer is then able to calculate the inter-landmark distances to all the references (Table 1). The inter-landmark distance of interest is saved, and this process is repeated for each individual landmark as required.

The computed dimensions can be of two types: the shortest distance between any two points, as used in this study, or the distance between points following a path over the surface. The chosen landmarks were comparable with anthropometric soft tissue cephalometric points. Some inter-landmarks distances identified on the 3D reconstruction are illustrated in Figure 4.

The reliability of interactive anatomic landmark localization and facial distance's measurement with the *VirSSPA* software was firstly evaluated in a 3D image of an unmarked anthropomorphic model by two independent observers. This situation most closely resembles the clinical application of the device for anthropometric assessment. The same anthropomorphic model was employed and both observers interactively identified and metered anthropometric landmarks on the 3D image without the aid of labels or other visual cues. Inter-observer reliability was assessed by collecting a subsample of 2 patients and repeated 9 inter-landmark measurements three times consecutively by two different investigators. A paired t-test was performed for these 18 measurements to determine whether significant differences between the mean of the 2 data existed.

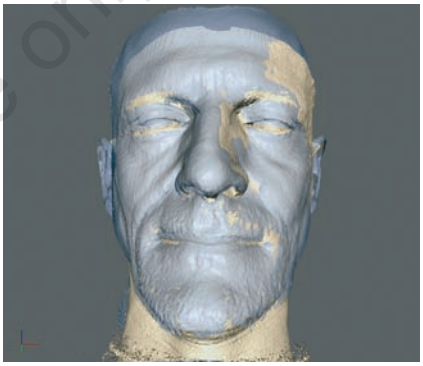


Figure 2. 3D facial reconstruction in patient number 2. White-light scanning image is represented in blue and CT image is flesh-colored. Both images are superimposed so that differences between them can be clearly seen.

Once determined the methodological accuracy, 3D images were reconstructed and the measurements recorded for use in the final statistical analysis. Nine measurements of different facial inter-landmark distances were taken in the sample of 3 patients. Distance measurements between the soft tissues selected points in the 3D facial reconstruction by *VirSSPA* and in the white-light scanning were compared with the exact findings on the patients (Table 2). All measurements were

Table 1. Anthropometric measurements.

Nº	Abreviations	Name
1	AI-AI	Nasal breadth
2	N-PG	Facial height
3	N-Ns	Nasal height
4	Po-AI	Camper´s plane
5	Po-GL	Distance between Po and GL
6	Po-PG	Distance between Po and PG
7	Po-N	Distance between Po and N
8	Po-Ns	Distance between Po and Ns
9	Zy-Zy	Facial breadth

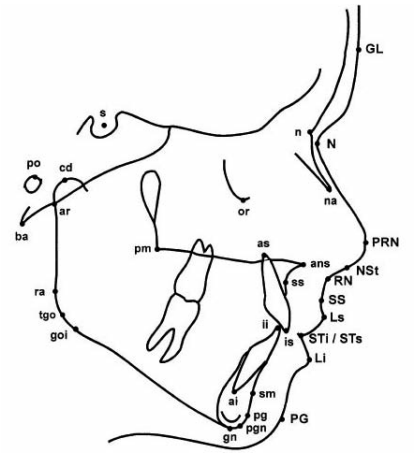


Figure 3. Cephalometric landmarks. Glabella (GL), the most prominent or anterior point in the midsagittal plane of the forehead at the level of the superior orbial ridges; soft tissue pogonion (PG), the most anterior point on the soft tissue chin in the midsagittal plane; soft tissue nasion (N), the deepest point in the soft tissue concavity overlying the frontonasal suture; nasal septum tangent point (NSt), the most anterior point on the columella of the nose, representing the anterior delimiter of the nasolabial angle; porion (po), the midpoint on the upper contour of the external auditory canal; ala insertion (AI), insertion point of the ala of the nose; zygion (Zy), most lateral point of zygomatic arch; pronasale (PRN), the most anterior point of the nasal tip; retronasale (RN), the junction of the columella of the nose with the philtrum of the upper lip.

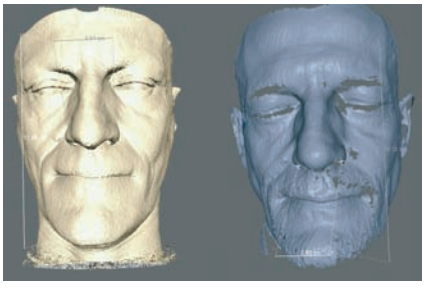


Figure 4. Some inter-landmarks distances identified on the 3D reconstruction both obtained by CT (left) and by white-light scanning (right) on the same patient.

repeated three times and the mean value was calculated in order to reduce errors.

Statistical analysis

The sample needed to fulfil the requirement for assessment of reliability of interactive 3D landmark localization study was 18 pairs of measurements by independent observers. The power of the test was set at 80 per cent and the level of significance 5 per cent. A paired t-test was performed for these 18 measurements to determine whether significant differences existed between the mean of the 2 data sets.

A Kolmogorov-Smirnov test was undertaken to reveal that all data were normally distributed. For comparative statistics a paired t-test was used. Statistical significance was considered to be $\alpha \leq 0.05$. Analysis of data was performed using the Statistical Package for the Social Sciences Windows version 15.0 (SPSS, Chicago, Illinois, USA).

Results

In order to determine whether significant differences existed between the mean values of the 2 data sets performed by independent observers, a paired t-test was performed for the 18 measurements required to assess the reliability of the landmark localization study. When the power of the test was set at 80 per cent and the level of significance 5 per cent ($P<0.05$) no statistically significant differences were found ($P>0.05$)-

The inter-landmark distances measured on facial models developed from CT aided with *VirSSPA* 3D software and white-light scanning were compared to the real human models. The sample was considered to follow a normal distribution after applying the Kolmogorov-Smirnov test.

We found that facial distances measured in the CT 3D reconstruction showed a mean error margin of 0.357 cm from the real distances measured on patients. On the contrary, mean error margin with the white-light scanning was of 0.096 cm. In both cases, measurements were found to be statistically significant ($P<0.05$).

Discussion

The psychological and social impact of the lipodystrophy syndrome on HIV-infected indi-

Table 2. Distance measurements between the soft tissues selected points in the 3D facial reconstruction with *VirSSPA* (from CT) and in the white-light scanning compared with the exact findings on the patients (considered to be the *gold standard*).

	Measurements	Gold_standard (Measurements in real patients)	VirSSPA (CT)	White-light scanning	Dif_VirSSPA (CT)	Dif_White-light scanning
Patient #1	1	2.10	2.02	2.12	0.08	0.02
	2	10.30	9.92	10.36	0.38	0.06
	3	4.60	4.20	4.70	0.40	0.10
	4	11.40	11.02	11.39	0.38	0.01
	5	12.60	12.20	12.51	0.40	0.09
	6	14.50	13.90	14.58	0.60	0.08
	7	12.00	11.82	12.05	0.18	0.05
	8	14.00	14.30	14.08	0.30	0.08
	9	7.60	7.20	7.60	0.40	0.00
Patient #2	10	1.80	1.75	1.81	0.05	0.01
	11	10.50	10.22	10.61	0.28	0.11
	12	5.00	5.02	4.92	0.02	0.08
	13	12.10	12.00	12.08	0.10	0.02
	14	13.30	13.05	13.12	0.25	0.18
	15	15.40	15.00	15.76	0.40	0.36
	16	12.60	12.30	12.86	0.30	0.26
	17	14.60	15.00	14.77	0.40	0.17
	18	10.80	10.20	10.87	0.60	0.07
Patient #3	19	2.18	2.06	2.17	0.12	0.01
	20	11.80	11.12	11.93	0.68	0.13
	21	6.40	5.60	6.25	0.80	0.15
	22	10.10	9.48	10.25	0.62	0.15
	23	12.40	12.19	12.36	0.21	0.04
	24	17.60	17.52	17.44	0.08	0.16
	25	12.50	11.70	12.56	0.80	0.06
	26	14.00	13.90	14.05	0.10	0.05
	27	9.20	8.50	9.10	0.70	0.10

viduals may be quite considerable and adversely affect their quality of life. Facial lipoatrophy is not only disfiguring but can also identify the HIV status of the individual in knowledgeable communities. The involuntary disclosure of the HIV condition can adversely impact on the patient as a result of discrimination and stigmatisation.[2-4] These patients have previously coped with HIV infection and, in the era of ART supply, while new hope is placed on the success of these therapies, the adverse effects may become discouraging.

To our knowledge, Ong *et al.*[9] are the only authors directly relating the use of 3D surface laser scanning to the surgical outcome in HIV facial lipoatrophy treated with facial implants. However, their report focused on clinical issues and psychological assessment before and after treatment.

Currently, a wide variety of technologies for digitally acquiring 3D model's shape is available. Established classifications divide them into two types: contact and non-contact 3D scanners[13] Non-contact 3D scanners can be further divided into two main categories, active and passive scanners. Active scanners emit some light and detect its reflection in order to capture an object or environment. Both surface laser scanning and structured light scanning can be distinguised within this category. Whereas surface laser scanners create a 3D model through laser projection and surface distance measurement, structured light scanners project a pattern of light and register pattern deformation on the object. Both technologies data are collected related to an internal coordinate system. When comparing both surface and structured light scanners, illumination level is an important requirement to be controlled in structured light scanner. Unsuitable illumination may produce spatial distortions in registered points. One of the biggest drawbacks of laser scanners is that recorded surfaces are obtained by means of several laser passes, *i.e.*, *painting* the object, so that redundancy in some areas may produce mesh fouling points and generate surface deformation. Furthermore, structured light scanners offer a higher performance on both image resolution and adquisition speed. Instead of scanning one point at a time, structured light scanners scan multiple points or the entire visual field at once. Thus reducing or even eliminating the distortion from motion problem. Therefore, and for the purposes of this paper, we selected structured light scanning as a more reliable method for 3D image acquisition than laser devices.

Over the past years, anthropometry has provided the most widely accepted and clinically useful method for quantitative assessment of facial surface anatomy.[14] This technique relies on the identification of standard soft-tissue landmarks and the direct measurement of distances, arcs, and angles between these points. However, direct anthropometry has several limitations as a method of clinical documentation of the face. The technique is restricted to the measurement of linear dimensions between landmarks and is inadequate for the task of 3D surface characterization and measurement.[14,15]

3D surface digitization constitutes a technology that rests upon the precise acquisition of topographic data in a digital format that can be interpreted by computer systems. The technique is entirely non-invasive and provides a non-contact acquisition of 3D data without distortion of the surface tissues being measured. However, accurate location of landmarks and operator skill are important factors to achieve reliable results with the obtained 3D models. In this paper, the reliability of interactive anatomic landmark localization has been evaluated in an unmarked head model under optimal scanning conditions. This reflects the ability of the user to visualize adequately anatomic landmarks on the computer image and to localize them without direct palpation of the surface. Surface landmarks are defined by their location at maximal concavities or convexities of the facial surface. Although readily identified by direct palpation in the real model, these points are identified less reliably by interactive visualization only. However, the use of a 3D cursor and real-time coordinates of the *VirSSPA* software improve the user's ability to identify these landmarks. Hence, *VirSSPA* software represents a reliable software for visualization and data measurement in white-light scanning surface tissues. Another potential attraction of our approach is that measurements of the facial fat loss volumes, which directly affects facial contour, might also be considered with such software in a similar way.

When compared to CT reconstructions, white-light scanning offers a more accurate landmark localization as well as reliable reconstructions of up to less than the tenth of a millimetre as average when compared to real measurements on facial human models. Facial white-light surface scanning is a repeatable and accurate method. On the contrary facial distances measured in CT show an average error of up to 3.5 mm. This technique is attractive because of its reliability, its performance takes a maximum of 2 min and does not involve either exposure to radiation or need for expert interpretation.[15] Nowadays, healthcare faces new challenges such as increased costs and the need to raise efficiency. The cost of one facial CT mapping is around 100 €(135 US$) in our hospital but it may vary depending on the institution concerned. Prices of 3D structured light scanning devices are comprised in a wide range between 10,000 and 75,000 €(13,700 to 105,000 US$) but once the equipment has been acquired 3D facial structured light scanning is cost-free. Structured ligth scanner used in this study had an average cost of 15,000 €(20,350 US$). Although only men were recruited to this study, the described technique should also be reproducible in women.

Despite the advantages of this technology in quantitative evaluation of the face, routine clinical application demands identification of sources of error and variability. Potential sources of error include biologic variation and the error associated with scanner digitalization. The pliability of facial soft tissues may result in subtle changes in the 3D surface associated with variations in expression, fatigue, and other image components. Despite a reportedly high spatial resolution, the ability of the scanner to accurately capture a three-dimensional surface varies with the quality of the surface, *i.e.*, the degree of topographical irregularity at any given point, the position and inclination of the object within the scanning field, and the optical properties of the object itself. Besides, it is important to highlight other potential causes of change in facial contour, such as hydration, facial hair, ageing and nutritional status. Changes as those mentioned, together with the sensitivity of the particular white-light scanner, may result overall in small differences between different scans. Therefore, further on-going studies are needed to definitively assess the usefulness of this tool in both research and clinical settings.

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