Volumetric Assessment of Pediatric Vascular Malformations Using a Rapid, Hand-Held Three-Dimensional Imaging System

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Abstract

The effect of percutaneous, surgical, and medical therapies for vascular malformations (VMs) is often difficult to quantify volumetrically using cross-sectional imaging. Volumetric measurement is often estimated with serial, expensive MRI examinations which may require sedation or anesthesia. We aim to explore whether a portable 3D scanning device is capable of rapid, accurate volumetric analysis of pediatric VMs. Using an iPad-mounted infrared scanning device, 3D scans of patient faces, arms, and legs were acquired over an 8-month study period. Proprietary software was used to perform subsequent volumetric analysis. Of a total of 30 unilateral VMs involving either the face, arms, or legs, 26 (86.7%) VMs were correctly localized by discerning the larger volume of the affected side compared to the normal contralateral side. For patients with unilateral facial VMs ($n = 10$), volume discrepancy between normal and affected sides differed compared with normal controls ($n = 19$). This was true for both absolute ($60 \text{ cc} \pm 55$ vs $15 \text{ cc} \pm 8$, $p = 0.03$) as well as relative ($18.1\% \pm 13.2$ vs $4.0\% \pm 2.1$, $p = 0.008$) volume discrepancy. Following treatment, two patients experienced change in leg volume discrepancy ranging from -17.3 to -0.4% . Using a portable 3D scanning device, we were able to rapidly and noninvasively detect and quantify volume discrepancy resulting from VMs of the face, arms, and legs. Preliminary data suggests this technology can detect volume reduction of VMs in response to therapy.

Keywords Vascular malformation · Volume assessment · 3D · Three-dimensional

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Introduction

Vascular malformations (VMs) represent a broad spectrum of congenital disorders ranging in severity from cosmetically displeasing to life-threatening. These malformations, which can involve any type of vessel including capillaries, lymphatics, veins, and/or arteries, affect nearly one in 22 children [1]. Given their morphologic diversity and complexity, VMs pose significant challenges to clinicians in terms of how they are assessed volumetrically for both determining disease severity and measuring response to treatment, when necessary. Currently, conventional cross-sectional imaging modalities such as MRI and CT are used for volumetric assessment of VMs; however, volume assessment is limited because of the pleomorphic appearance of these malformations. MRI has shown the most promise in terms of providing reproducible, objective data that correlates to clinical measures and functional outcomes of treatment [2, 3]. However, no single imaging method has been widely adopted and most approaches are labor intensive and subject to error as they require human interpretation. Further limitations of MRI and CT include need

for sedation, particularly for younger children, and ionizing radiation, respectively. As such, clinicians are often left to highly subjective methods for evaluating VMs including photographic documentation and clinical scoring instruments [4], which compliment clinical assessment.

Recent improvements in three-dimensional imaging (3DI), such as stereophotogrammetry and laser scanning, have led to numerous applications of these technologies for volumetric and morphologic assessment of surface structures. One of the most common applications of 3DI, and where a majority of evidence exists supporting its validity, is in the realm of postoperative swelling following oral and maxillofacial surgery [5–7]. More recently, 3DI systems have been applied to the extremities. These systems have been used for quantification of post-mastectomy upper extremity lymphedema and have even shown greater reliability compared to traditional methods of volume assessment such as circumferential and water displacement measurements [8, 9]. In addition, 3DI has been used to assess lower-extremity lymphedema resulting from conditions ranging from chronic venous insufficiency to lymphatic filariasis [10, 11].

Given the emerging body of evidence supporting the use of 3DI for volumetric assessment of the head and neck as well as the extremities, it seems plausible that this technology could be used to evaluate pediatric VMs which can occur in any body region. Thus, the aim of this study is to determine if 3DI can be used for rapid, noninvasive volumetric assessment of pediatric VMs enabling quantification of disease severity and response to treatment.

Materials and Methods

Patient Selection

All protocols and procedures were approved by the Children's Healthcare of Atlanta Institutional Review Board (IRB). Patients were enrolled in the study after obtaining informed consent as well as assent when applicable. In order to be included in the study, patients had to (i) be less than 21 years of age, (ii) have a VM involving the head, neck, or extremities, and (iii) be receiving routine care through our institutional, multidisciplinary Vascular Anomalies Clinic (VAC). Even patients with morphologically subtle VMs were included. VM types included venous malformations, lymphatic malformations, and arteriovenous malformations, as well as overgrowth syndromes with associated vascular malformations such as Klippel-Trenaunay syndrome (KTS). Control patients had to (i) be less than 21 years of age, (ii) not have a VM involving the scanned area, and (iii) be receiving routine care through the VAC.

Scanning Technology

The 3DI system employed for this study was a Structure Sensor (Occipital Inc., San Francisco, CA, USA) mounted to an Apple iPad Mini 2 (Apple Inc., Cupertino, CA, USA) tablet. The device, which costs \$379 (USD), consists of an infrared structured light scanner whereby a pattern of infrared light is projected onto the surface of an object and the 3D shape of the object is derived from the distortion of the projected pattern. The Structure Sensor uses an FDA Class 1 Laser which, by definition, is considered non-hazardous under all conditions of normal use. After acquisition, scans were uploaded to a secure database meeting Health Insurance Portability and Accountability Act (HIPAA) standards.

Patient Scanning

Patient scans were completed from May 2017 through December 2017 in either the VAC or in a preprocedural holding area if a patient was in the hospital to undergo a procedure with interventional radiology (IR). Regardless of the setting, scans were completed in a private room. Scans were completed by one of two members of the study team (E.S and S.P.) who received adequate training with the scanning device and protocols prior to scanning patients.

For head and neck scans, the patient was asked to assume a natural head position with eyes closed as this has been shown to be clinically reproducible [12]. To reduce scanning artifact, patients were asked to remove glasses, piercings, or any other objects in the scanning area. In addition, the patient was asked to adjust their hair to minimize the amount that would obscure the face. The examiner would then stand 3–4 ft in front of the patient, direct the tablet towards the patient's head, and use a superimposed sizing box projected within the customized acquisition software (LymphaTech, Atlanta, GA) to ensure that the entire head and neck were included in the scanning zone. The examiner would then begin to acquire the scan while panning the tablet around the patient. The examiner is able to confirm the quality of the scan in real-time as the software depicts the 3D scan overlying an image of the patient as the scan is being acquired.

Arm and leg scans were acquired in a similar fashion. For arm scans, the patient was asked to hold their arm parallel with the floor with their palm facing forward. Each arm was scanned separately ensuring that the scanning zone incorporated the entire arm. A pole upon which the patient could grasp was employed in order to reduce motion artifact as well as any discomfort experienced from holding the arm in position. Legs scans were obtained by having the patient remove socks and shoes and stand with feet shoulder-width apart.

In general, scans were able to be acquired in a minute or less. Duplicate scans, or repeat scans completed in the same encounter, were obtained whenever possible in order to determine intra-operator variability. However, this was not always feasible due to time constraints encountered during some patient visits.

Processing Patient Scans

Head/Neck Scans

One scan from each patient was first imported into MeshLab (Online Resource 1a) (Visual Computing Lab, Pisa, Italy), an open-source, 3D mesh processing tool [13]. The scan was then manually aligned using the manipulator tool in order to correct for any postural deviations from natural head position such that the sagittal and transverse plans were parallel with the vertical and horizontal axes, respectively (Online Resource 1b). Next, any additional scans of that patient, either duplicate scans or follow-up scans, were aligned to this “reference scan” using the Point-based Gluing Alignment tool of MeshLab. This tool uses four or more user-selected points to approximate the alignment of a scan to an established reference (Online Resource 1c-e). Generally, six points were manually selected for optimal alignment: left and right earlobe, left and right eye, forehead, and chin. When necessary, patient hair obscuring the face was digitally removed.

After all scans of a patient were aligned, a single scan was then analyzed using proprietary software (LymphaTech, Atlanta, GA, USA) run on a MATLAB (Mathworks, Natick, MA, USA) platform. User-defined index points were visually selected on this initial scan in order to identify the region of interest from which volume measurements are derived. For the purposes of this study, the boundaries of the face were defined as follows: superiorly by the level of the eye, inferiorly by the chin, anteriorly by the tip of the nose, and posteriorly and laterally by the anterior crease of the earlobes (Fig. 1a). After the user defined this region, they were then prompted to select the midpoint of the nose. This point creates a sagittal plane that bisects the selected region into left and right sides enabling volume comparison of the respective sides (Fig. 1b). Coordinates from each of the user-defined index points were logged and, for all subsequent scans of that patient, these exact coordinates were used to ensure the highest degree of consistency in identifying the region of interest across all scans taken of an individual patient.

For the few patients whose VM was localized to the periorbital or cervical region, different boundaries defined the area of interest. The periorbital region was defined superiorly by the brow-line, inferiorly and anteriorly by the inferior border of the nose, and posteriorly and laterally

by the temples (Online Resource 2a-b). The cervical region was defined superiorly and anteriorly by the chin, inferiorly by the midpoint of the sternoclavicular joint, and posteriorly by the most posterior aspect of the neck (Online Resource 2c-d).

Arm Scans

For VMs involving the entire upper extremity, the region of interest was defined proximally by the axilla and distally by the wrist. These boundaries were automatically determined by LymphaTech software which is capable of localizing the wrist and axilla using circumferential data. If the VM involved only the forearm, only the region defined proximally by the elbow and distally by the wrist was analyzed. For VMs involving only the upper arm, the region bound by the axilla and elbow was analyzed. The elbow was manually identified by the flexural crease of the antecubital fossa.

Leg Scans

For VMs involving the entire lower extremity, the region of interest was defined inferiorly by the floor and superiorly by the axial plane in which either the thighs came together medially or there was interference from an item of clothing. If a VM exclusively involved the leg below the knee, a superior boundary of the infrapatellar plane was used. The infrapatellar plane was defined by the level of leg where circumference is at a minimum, just distal to the insertion of the patellar tendon. For lesions localized above the knee, the inferior boundary was defined by the infrapatellar plane.

Analysis

Statistical analysis was completed using JMP Pro, Version 13.0.0 (SAS Institute Inc., Cary, NC, USA). A two-tailed Student *t* test was used to compare volumetric means, with significance established at $p = 0.05$. Relative volume discrepancy between left and right sides was calculated using the formula $\text{Volume}_{\text{relative}} = (V_a - V_b)/V_b$, where V_a is the side with the larger volume and V_b is the contralateral side. For patients with a lateralized VM, the side with the larger volume was often the affected side.

Results

Patient Characteristics

A total of 67 patients were enrolled in the study and subsequently scanned. Mean patient age at the time of enrollment

Fig. 1 **a** The region of interest (red) for the face is manually identified with boundaries defined superiorly by the level of the eye, inferiorly by the chin, anteriorly by the tip of the nose, and posteriorly and laterally by the anterior crease of the earlobes. **b** The region of interest is then bisected

to allow for volume comparison of left and right sides. The sagittal plane is created using input from a user-defined midpoint of the nose. **c** A cross-sectional view of the region of interest

was 11.2 years (± 4.6 ; range, 1–19.3 years). The various types and location of VMs are listed in Online Resource 3, Table S3.

Scanning

Although a total of 250 scans were completed throughout the study period, 98 scans from 35 patients were excluded from the analysis. Scans were excluded due to various reasons including inability to analyze region of interest with existing protocols ($n = 61$). For example, the protocols used were unable to accurately derive volumes from the hands, feet, and trunk. As such, patients with VMs extending into these regions were excluded. Other reasons for patient exclusion included lack of contralateral limb for comparison ($n = 18$), poor-quality scan ($n = 11$), hair obscuring region of interest ($n = 6$), and poor patient positioning ($n = 2$). Among the 152 scans included in the study, there were 97 head and neck, 16 individual arms, and 39 leg pairs.

Head/Neck

Given the inherent subjectivity in user-defined index points, the resulting degree of variability in volumetric data was first to be quantified. To do this, faces from five head and neck scans of control patients were each analyzed 10 separate times to determine intraoperator variability. Despite minimal variability in user-defined index points, ranging from 0.3–4.6 mm, relative and absolute volume discrepancies for each set of

patient analyses ranged from 3.6–8.7% and 11–31 cc, respectively (Online Resource 3, Table S2). This range of values suggest that index points are selected with greater reproducibility in certain patients, likely those with more defined anatomic landmarks [14]. Since exact coordinates for user-

Fig. 2 A box-and-whisker plot demonstrating relative volume discrepancy between left and right sides of the face in control patients compared to patients with unilateral facial VMs. The box defines the middle two quartiles and whiskers define the full range of data including outliers. A scatter plot of individual volume discrepancy values is shown in ghost form

defined index points were used to define the region of interest for all duplicate patient scans, minimal variability in volumetric data was expected across duplicate scans. This was in fact the case as relative and absolute volume discrepancies varied on average only 1.9% (range, 0.2–6.3%) and 5 cc (range, 1–16 cc) across duplicate scans, respectively.

In order to determine if scans were able to distinguish between study and control patients, volume discrepancy between left and right sides of the face was calculated for all patients with unilateral facial VMs ($n = 10$) along with normal controls ($n = 19$). A significant difference was found between study and control patients in terms of both absolute ($60 \text{ cc} \pm 55 \text{ cc}$ vs $15 \text{ cc} \pm 8 \text{ cc}$, $p = 0.03$) as well as relative ($18.1\% \pm 13.2\%$ vs $4.0\% \pm 2.1\%$, $p = 0.008$) volume discrepancy (Fig. 2). These absolute and relative volume

discrepancies were also significantly larger ($p = 0.04$ and $p = 0.01$, respectively) than those due to intraoperator variability associated with the manual selection of anatomic landmarks, suggesting that variability due to landmark selection has minimal effect on assessing the VM. Relative volume discrepancy of study patients was then plotted in order, ranging from volumes favoring the left side of the face to those favoring the right, to demonstrate that these values correlate well with morphological severity of the VM (Fig. 3). Overall, there was good correlation between the side with the greater volume and the side affected by the VM allowing for 7/10 (70%) of VM to be localized to the correct side using volume data. However, there were three patients (VA034, VA032, and VA039) in which the unaffected side actually had a larger calculated volume. Of

Fig. 3 **a** Renderings of 3D scans taken from patients with unilateral facial VMs alongside **b** cross-sectional views of the region of interest with an asterisk (*) demarcating the affected side. **c** Relative volume discrepancy, defined as percent difference of the side with a larger volume compared to the contralateral side, is shown for each corresponding patient

note, one of these patients (VA034) had a visually undetectable VM and another (VA039), interestingly, does in fact appear to have greater volume on the side of the face unaffected by the VM.

To determine the feasibility of this approach to capture changes in VM severity over the course of treatment, three study patients were administered follow-up scans 12–19 weeks after receiving percutaneous sclerotherapy for their unilateral facial VM. Change in relative volume discrepancy ranged from -0.4 to $+2.7\%$. However, these changes in volume discrepancy did not differ significantly compared to changes seen in four control patients who underwent scans over a similar time period ($p = 0.10$). In addition, these changes did not differ from the degree of intraoperator variability seen within duplicate scans taken over the treatment period ($p = 0.23$).

Two patients had VMs involving only the eye. Relative and absolute volume discrepancies were calculated for the periorbital region of these patients and compared to the periorbital region of two normal controls. Among this limited cohort of patients, no significant difference in either relative ($p = 0.39$) or absolute volume discrepancy ($p = 0.38$) was seen between study and control patients.

Scans of patients with VMs involving the neck ($n = 3$) were unable to be processed with the protocol developed for analyzing the face. This is likely due to the region of interest used to define the cervical region being heavily affected by patient positioning and easily obscured by patient hair.

Arms/Legs

Scans from five patients with VMs involving one arm were analyzed. Two patients had involvement of the entire extremity, two had involvement of only the upper arm, and one had involvement of only the forearm (Fig. 4). VMs were correctly localized in 4/5 (80%) patients by detecting increased volume of the affected limb. Relative and absolute volume discrepancies between the affected and normal arm were $19.7\% \pm 14.2\%$ and $167 \text{ cc} \pm 153 \text{ cc}$, respectively.

Scans from 15 patients with unilateral leg VMs were analyzed. Eight patients had involvement of the entire extremity, four had involvement of only the upper leg or thigh, and three had involvement of only the lower leg. VMs were correctly localized in 15/15 (100%) of patients with an average relative and absolute volume discrepancy of $19.6\% \pm 29.9\%$ and $603 \text{ cc} \pm 901 \text{ cc}$, respectively. Again, relative volume

Fig. 4 Renderings of 3D scans of patient arms along with circumferential outputs from LymphaTech software. An anterior and superior view is shown of each scanned arm region, and an asterisk (*) indicates the side affected by a VM. **a** Scans of the forearm completed for a patient who has a venous malformation involving the right forearm and elbow. **b** Upper arm scans of a patient with a venous malformation involving the right bicep. **c** Whole arm scans for a patient with glomuvenous malformation involving the entire extremity

discrepancy correlated well with the morphological severity of the VM (Fig. 5). Two patients completed follow-up scans after receiving treatment for their VM. One patient, who underwent embolization and subsequent surgical resection for a vascular hamartoma, had a reduction in relative volume discrepancy from 3.7 to 3.3%. However, this small reduction may be attributable to or affected by intrinsic error of the technique. Another patient with KTS had follow-up scans after completing 15 weeks of medical therapy with rapamycin. The patient had a reduction of relative volume discrepancy from 112.6 to 95.3% over this time period (Fig. 6).

Discussion

The purpose of this study was to determine whether a portable 3D scanning device is capable of rapid and reproducible volumetric analysis of pediatric VMs. A fundamental step in

determining this was to first demonstrate that this technology is able to correctly identify the laterality of the VM. Of a total of 30 unilateral VMs involving either the face, arms, or legs, 26 (86.7%) VMs were correctly localized by discerning the larger volume of the affected side compared to the normal contralateral side. In addition, we were able to show that relative volume discrepancy correlates well with morphological severity of VMs.

By calculating relative volume discrepancy of control patients, we found that 19/19 (100%) of normal faces have a relative volume discrepancy of < 10%. This threshold has a sensitivity for detecting 8/10 (80%) of unilateral facial VMs included in this study. This threshold may be useful as a clinical endpoint for percutaneous or medical treatment of facial VMs. For example, although clinical symptomatology often informs therapy decisions, a clinician may decide to not pursue any further sclerotherapies for a patient with a venous malformation involving the left face if the patient has a reduction of relative volume discrepancy to less than 10% following treatment.

Another main purpose of this study was to determine if our 3DI system is able to detect the expected volume reduction of VMs in response to treatment. A major limitation of this study, and the direct consequence of a short study period, was the limited number of patients who had follow-up scans after undergoing treatment. Of the three patients with facial VMs who completed the follow-up scans after undergoing treatment, reduction in volume discrepancy did not differ significantly compared to that seen among control patients. However, given that follow-up scans were completed just 12–19 weeks after baseline scans, it is unlikely that substantial volume reductions would have been observed. In addition, the patients underwent only 1 or 2 percutaneous sclerotherapies over the treatment period, whereas patients will often require numerous interventions before there is noticeable reduction in the size of VMs. More promising were the patients with leg VMs who both showed a reduction in volume discrepancy with one experiencing a notable 17.3% reduction in response to medical therapy.

As with any other feasibility study, this study was not without other limitations. In addition to limited follow-up data within the study group, there was a lack of control arm and leg scans. Although using a patient's unaffected limb as an internal control allowed for quantification of volume discrepancy, without a group of arm and leg control patients, we were unable to establish the normal amount of relative volume difference between corresponding limbs. There are also inherent limitations in how scans were processed. For example, intraoperator variability across user-defined index points used to define boundaries of the region of interest undoubtedly had some degree of impact on the resulting volumetric data. Further efforts must be made in order to automate the selection of the region of interest in order to reduce user variability.

Fig. 5 **a** Renderings of 3D scans taken from patients with unilateral whole leg VMs. **b** Relative volume discrepancy, defined as percent difference of the side with a larger volume compared to the contralateral side, is shown for each corresponding patient

Fig. 6 Renderings of 3D scans along with circumferential data used to derive leg volumes are shown in a patient with KTS affecting the left leg before (a) and after (b) completing 15 weeks of medical therapy with rapamycin. Although circumferences of the right leg remain unchanged,

the affected leg shows a decrease in circumferences most notably above the knee. This is consistent with a calculated reduction in relative volume discrepancy by 17.3%

There are additional potential pitfalls in the concept of 3DI-based volumetric analysis. One such pitfall is that absolute volume is invariably affected by normal growth of patients. Although using relative volume discrepancy helps to normalize the expected volume increase, normal growth may mask true volume reduction in response to treatment in the pediatric population. Another limitation of a 3DI system is that deep VMs with little or no surface manifestations cannot be accurately assessed. Finally, a VM involving a limb may result in some degree of atrophy if it is painful or burdensome for the patient to use the affected limb. This would, in turn, affect relative volume comparison to the contralateral side.

Conclusion

We were able to use a portable 3DI system to rapidly and noninvasively detect and quantify volume discrepancy resulting from VMs of the face, arms, and legs. Preliminary data suggests this technology will be able to detect volume

reduction of VMs in response to standard therapies, though further investigation is needed to fully demonstrate this capability. The implications of such capabilities could be clinically significant. By reducing or eliminating the need for serial MRIs, this 3DI system could result in considerable cost savings [15]. Given its ease of use and increasing availability, this 3DI system may be used in an outpatient setting rather than requiring patients to travel to an imaging center. This would provide greater convenience to patients along with additional data on their VM throughout the treatment period. Finally, this modality may enable clinicians to more accurately compare the effects of different therapeutic approaches to treating VMs [16].

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References

1. Buckmiller LM, Richter GT, Suen JY: Diagnosis and management of hemangiomas and vascular malformations of the head and neck. *Oral Dis.* 16(5):405–418, 2010
2. Alexander MD, McTaggart RA, Choudhri OA et al.: Quantitative volumetric analysis of head and neck venous and lymphatic malformations to assess response to percutaneous sclerotherapy. *Acta Radiol.* 57(2):205–209, 2016
3. Caty V, Kauffmann C, Dubois J, Mansour A, Giroux MF, Oliva V, Piché N, Therasse E, Soulez G: Clinical validation of semi-automated software for volumetric and dynamic contrast enhancement analysis of soft tissue venous malformations on magnetic resonance imaging examination. *Eur Radiol.* 24(2):542–551, 2014
4. Kirkham EM, Edwards TC, Weaver EM, Balakrishnan K, Perkins JA: The lymphatic malformation function (LMF) instrument. *Otolaryngol Head Neck Surg.* 153(4):656–662, 2015
5. Harrison JA, Nixon MA, Fright WR, Snape L: Use of hand-held laser scanning in the assessment of facial swelling: a preliminary study. *Br J Oral Maxillofac Surg.* 42(1):8–17, 2004
6. Kau CH, Cronin AJ, Richmond S: A three-dimensional evaluation of postoperative swelling following orthognathic surgery at 6 months. *Plast Reconstr Surg.* 119(7):2192–2199, 2007
7. van der Meer WJ, Dijkstra PU, Visser A, Vissink A, Ren Y: Reliability and validity of measurements of facial swelling with a stereophotogrammetry optical three-dimensional scanner. *Br J Oral Maxillofac Surg.* 52(10):922–927, 2014
8. Hameeteman M, Verhulst AC, Vreeken RD, Maal TJ, Ulrich DJ: 3D stereophotogrammetry in upper-extremity lymphedema: an accurate diagnostic method. *J Plast Reconstr Aesthet Surg.* 69(2):241–247, 2016
9. Cau N, Galli M, Cimolin V, Grossi A, Battarin I, Puleo G, Balzarini A, Caraceni A: Quantitative comparison between the laser scanner three-dimensional method and the circumferential method for evaluation of arm volume in patients with lymphedema. *J Vasc Surg Venous Lymphat Disord.* 6(1):96–103, 2018
10. Mestre S, Veye F, Perez-Martin A, Behar T, Triboulet J, Berron N, Demattei C, Quéré I: Validation of lower limb segmental volumetry with hand-held, self-positioning three-dimensional laser scanner against water displacement. *J Vasc Surg Venous Lymphat Disord.* 2(1):39–45, 2014
11. Yahathugoda C, Weiler MJ, Rao R, de Silva L, Dixon JB, Weerasooriya MV, Weil GJ, Budge PJ: Use of a novel portable three-dimensional imaging system to measure limb volume and circumference in patients with filarial lymphedema. *Am J Trop Med Hyg.* 97(6):1836–1842, 2017
12. Kau CH, Hartles FR, Knox J, Zhurov AI, Richmond S: Natural head posture for measuring three-dimensional soft tissue morphology. Cardiff: FIRST Numerics, 2005
13. Cignoni P, Callieri M, Corsini M, Dellepiane M, Ganovelli F, Ranzuglia G: Meshlab: an open-source mesh processing tool. Paper presented at: Eurographics Italian Chapter Conference, 2008.
14. Toma AM, Zhurov A, Playle R, Ong E, Richmond S: Reproducibility of facial soft tissue landmarks on 3D laser-scanned facial images. *Orthod Craniofac Res* 12(1):33–42, 2009
15. Knoops PG, Beaumont CA, Borghi A et al.: Comparison of three-dimensional scanner systems for craniomaxillofacial imaging. *J Plast Reconstr Aesthet Surg* 70(4):441–449, 2017
16. Berenguer B, Burrows PE, Zurakowski D, Mulliken JB: Sclerotherapy of craniofacial venous malformations: complications and results. *Plast Reconstr Surg* 104(1):1–11, 1999 discussion 12–15