Creating a Map of Adipose Tissue Distribution and Automated Fat Volume Analysis for Plastic Surgery

Robert Harutyunyan

Department of Experimental Surgery,

McGill University,

Montreal, Québec, Canada

July 2022

A thesis submitted to McGill University in Partial Fulfillment

of the Requirements for the Degree of

Master of Science

"If you look at history, innovation doesn't come just from giving people incentives; it comes from creating environments where their ideas can connect."

- Steven Johnson

Abstract

Background: Adipose tissue plays a fundamental role in plastic surgery, extending from fat extraction via liposuction to the transfer of vascularized flaps for oncologic and reconstruction purposes. Procedures involving fat manipulation, such as liposuction, contain a degree of subjectivity mainly guided by the surgeon's visual or tactile assessment of the underlying fat. This acquired sense dictates procedural behaviour where errors commonly result in body contour irregularities and, in rare cases, potentially lethal complications such as pulmonary/fat embolism, necrosis and perforation of abdominal organs. There is a gap in the current literature regarding objective measurement procedures that incorporate subcutaneous adipose tissue (SAT) volume in an intra-operative, rapid, dynamic, and cost-efficient approach. The authors aim to develop and validate a web-based platform with innovative ultrasound-based software in which clinically accurate fat tissue volume and distribution measurements can be effectively estimated and simulated in the pre-operative setting.

Methods: In the first phase of this thesis, the focus was placed on constructing a novel web-based platform in which ultrasound measurements can easily be integrated to build 2D and 3D models of soft tissues. The current software, SAT-Map, was adapted for liposuction procedures to test its accuracy and feasibility. Liposuction was chosen as the default proxy procedure due to the ability to readily correlate ultrasound measurements with extracted volumes of fat in lipoplasty canisters. In the second phase, the pilot trial recruited 18 participants at a plastic surgery clinic associated with McGill University Health Center. All participants underwent ultrasound scans of the study area, according to the operational manual, before surgery. Estimated fat profiles were generated using SAT-Map, and then the agreement was compared directly with the intra-operative aspirated fat recorded after gravity separation.

Results: The SAT-Map platform was constructed with an intuitive design and straightforward method of generating patient-specific models. The system can support fat profiles from any

anatomical location in a grid-like representation in 2D and 3D. Additionally, the virtual models are interactive heatmaps which can be rotated to display various orientations of the soft tissues. Following the pilot trial, a Bland Altman statistical analysis was performed to determine the agreement between the new software and liposuction results. The analysis indicated that 43/44 measurements fell within an agreement of 95% compared to the clinical lipoaspirate (dry) volumes collected post-surgery. The bias was calculated at 9.15 mL with a standard deviation of 17.08 mL and 95 % confidence limits of -24.34 mL and 42.63 mL. The encouraging results suggest that ultrasound estimation using SAT-Map is a technique worth investigating further for plastic surgery applications.

Conclusion: SAT-Map is the first combined software that objectively measures and simulates fat distribution and volume. As a user-friendly and web-based tool offering multiple advantages over current methods of SAT assessment, ultrasonography proved to be an excellent adjunct to SAT-Map. Overall, this thesis project has taken a step forward in the concept of objective fat quantification toward improving patient conversation, surgical outcomes, and satisfaction in liposuction procedures. This notion was strengthened by the pilot trial showing that pre-operative fat assessment measurements agreed significantly with intraoperative lipoaspirate volumes. The work completed will surely be a bridge towards evolving current methods for liposuction and simultaneously developing protocols for other procedures that involve fat manipulation. Ultimately, this novel modality of an established tool is an example of evolving applications of technology in healthcare that provide better feedback and guidance to patients and surgeons alike.

Résumé

Contexte: Le tissu adipeux occupe une fonction fondamentale en chirurgie plastique, allant de l'extraction de graisse par liposuccion jusqu'au transfert de greffons vascularisés à des fins oncologiques et de reconstruction après une blessure traumatique. Les procédures qui nécessitent une manipulation de la graisse, comme la liposuccion, contiennent un degré de subjectivité principalement guidé par l'évaluation visuelle ou tactile de la graisse par le chirurgien. Ce jugement dicte le comportement procédural, dont les erreurs entraînent souvent des imperfections du contour du corps et, dans de cas plus rares, des complications potentiellement fatales. Il existe une lacune dans la littérature actuelle concernant les procédures de mesure objective qui intègrent le volume du tissu adipeux sous-cutané dans une approche per-opératoire, rapide, dynamique et économique. Les auteurs ont pour objectif de développer et de valider une interface sur le web avec un logiciel innovant basé sur les ultrasons dans lequel des mesures cliniquement précises du volume et de la distribution du tissu adipeux peuvent être efficacement estimées et simulées dans le cadre pré-opératoire.

Méthodes: Dans la première phase de cette thèse, les efforts se sont concentrés sur la construction d'une nouvelle technologie basée sur le web dans laquelle les mesures ultrasonores peuvent facilement être intégrées pour construire des modèles 2D et 3D de tissus mous. La liposuccion a été choisie comme procédure de référence en raison de la possibilité de corréler facilement les mesures ultrasonores avec les volumes de graisse extraits dans les contenants de lipoplastie. Dans la deuxième phase, le projet pilote a recruté 18 participants dans une clinique de chirurgie plastique associée au Centre Universitaire de Santé McGill. Tous les participants ont reçu des échographies de la zone d'étude, conformément au manuel opérationnel, avant la chirurgie. Les profils adipeux estimés ont été générés à l'aide de SAT-Map, puis leur accord a été comparé directement avec la graisse aspirée enregistrée après séparation par gravité.

Résultats: L'interface SAT-Map a été construite de manière intuitive pour simplement générer des modèles spécifiques au patient. Le système peut prendre en charge les profils de graisse de n'importe quel emplacement anatomique dans une représentation en grille en 2D et 3D. En outre, les modèles virtuels sont des cartes thermiques interactives qui peuvent être pivotées pour afficher différentes orientations des tissus. Après le test pilote, une analyse statistique Bland Altman a été réalisée pour déterminer la concordance entre le nouveau logiciel et les résultats de la liposuccion. L'analyse a indiqué que 43/44 mesures se situaient dans une marge de concordance de 95 % par rapport aux volumes cliniques de lipoaspirats (secs) recueillis après l'intervention. Le biais a été calculé à 9,15 ml avec un écart standard de 17,08 ml et des limites de confiance à 95 % de -24,34 ml et 42,63 ml. Ces résultats encourageants suggèrent que l'estimation par ultrasons à l'aide de SAT-Map est une technique qui mérite d'être approfondie pour les applications en chirurgie plastique.

Conclusion: SAT-Map est le premier logiciel combiné qui mesure objectivement et génère une simulation de la distribution et du volume de la graisse. Ce projet a permis d'avancer le concept de la quantification objective de la graisse afin d'améliorer la conversation avec les patients, les résultats chirurgicaux et la satisfaction dans les procédures de liposuccion. Cette notion a été renforcée par le test pilote montrant que les mesures d'évaluation de la graisse pré-opératoire concordaient significativement avec les volumes de lipoaspiration opératoires. En fin de compte, cette nouvelle modalité d'un outil établi est un exemple des nouvelles applications de la technologie dans les soins de santé qui fournissent un meilleur retour d'information et des conseils aux patients et aux chirurgiens.

Table of Contents

List of Abbreviations

US: Ultrasound

CT: Computed Tomography

MRI: Magnetic Resonance Induction

BMI: Body Mass Index

SAT: Subcutaneous Adipose Tissue

2D: Two-Dimensional

3D: Three-Dimensional

L: Length

W: Width

CI: Confidence Interval

FSA: Fat Safety Assumption

Cm: Centimeter

List of Figures

Chapter 2

Chapter 3

List of Tables

Acknowledgements

During these unique times as a result of Covid-19, the importance of morale and adaptability are essential for fostering and striving toward success. The work presented is the result of the combined support and direction from my supervisors and the support of outstanding lab members who have been critical to the realization of this thesis.

I would like to first acknowledge my supervisors, **Dr. Mirko Gilardino** and **Dr. Thomas Hemmerling**, for their guidance and mentorship over the last two years. I extend my utmost gratitude for offering the opportunity to work on such an exciting and innovative project. Due to their continuous desire to innovate, support and impart wisdom, I have been able to bring this thesis to completion. I will always admire their passion and devotion to surgical innovation.

A special mention goes out to **Dr. Shantale Cyr** for her continuous support during the pandemic, which has made access to many resources unexpectedly challenging. It is clear that without her excellent management and assistance, much of the work in this thesis would not have come to fruition.

In addition, I would like to extend a special thanks to my Research Advisory Committee (RAC) members, **Dr. Louis-Nicholas Veilleux**, **Dr. Andreas Nikolis** and **Dr. Joshua Vorstenbosch,** for their expertise, feedback, and valuable input throughout my master's degree.

During these extraordinary times, a final thanks to my family, fiancée and fellow lab mates for their friendship and love.

Contribution of Authors

Chapter 2 - Article 1:

Robert Harutyunyan: Responsible for designing, developing, testing the software and writing the manuscript.

Yichen Wu: Helped with software development and design.

Sean Jeffries: Helped with software development and design.

Dr. Thomas Hemmerling and Dr. Mirko Gilardino: Responsible for conceiving the study and revising the manuscript.

9330-7353 Qc Inc.: Financial support for the development of technology via the Mitacs Accelerate grant.

Chapter 3 - Article 2:

Robert Harutyunyan: Responsible for designing and conducting the pilot trial, performing the statistical analysis, and writing the manuscript.

Dr. Vasilios Papanastasiou: Helped conduct the pilot trial.

Dr. Mirko Gilardino and **Dr. Thomas Hemmerling:** responsible for conceiving the study, overseeing the trial, and revising the manuscript.

9330-7353 Qc Inc.: Financial support for the development and testing of new technology via the Mitacs Accelerate grant.

Chapter 1 – Introduction

As modern surgery evolves, new innovative technologies are gradually changing the practice of surgery with the aspiration of improving the quality of care. In the grand landscape of surgery, the emergence of new imaging techniques, computer-based technologies, and virtual simulations provide a means to evaluate objectively and pre-operatively plan for complex surgical procedures. For specialists in plastic surgery, certain fields, such as craniofacial surgery, have paired imaging systems with computer-based technologies to create 3D cranial models to plan upcoming reconstructive and aesthetic surgeries effectively.[1] This novel approach has transformed the subjective task of determining the degree of head deformity into an accurate translation of pre-operative surgical planning toward optimizing patient outcomes.[2] Fundamentally, surgeons must have precise knowledge of anatomy at any surgical site. However, innovative solutions such as these have not been applied ubiquitously in plastic surgery. In fat transfer-based procedures such as liposuction, subcutaneous adipose tissue (SAT) is generally assessed using subjective methods such as visual or tactile examination of the underlying fat (i.e., pinch test). This acquired judgment dictates surgical decision-making where anatomical ambiguity can lead to contour irregularities or, in rare cases, potentially lethal complications such as pulmonary/fat embolism, necrosis and perforation of abdominal organs.[3] Taking this into consideration, there is a current need for an objective measurement modality incorporating SAT quantification, given the significance of adipose tissue in fat removal, fat grafting, and the transfer of vascularized flaps for reconstruction purposes.[3-5] Moreover, the introduction of clinically accurate virtual simulation of the underlying soft tissues would further benefit pre-operative planning, surgical outcomes and patient satisfaction.

Imaging techniques such as Magnetic Resonance Imaging (MRI) and Computed Tomography (CT) offer an excellent characterization of soft tissues and can deliver objective measurements of adipose tissue thickness.[6,7] However, these techniques are complex, time and resource intensive, and are not readily available.[8] Alternatively, ultrasonography (US) represents an additional validated method for SAT assessment with comparable performances to MRI and CT.[9-11] Advantages to the US include a radiation-free modality that is accessible, cost-effective, rapid and portable.

Amidst the significant role of adipose tissue in plastic and reconstructive surgery, this thesis project aimed to contribute new insight in SAT quantification for objective pre-operative planning. The approach was to construct and validate the first web-based software that utilizes US imaging to quantify and simulate clinically accurate fat distribution and volume. Ultimately, this novel companion tool aims to support surgeons by providing a user-friendly platform to increase surgical success and patient satisfaction.

Chapter 2 – Article 1

Description of a Novel Web-Based Liposuction System to Estimate Fat Volume and Distribution

Author list: Robert **Harutyunyan**, BSc[1]; Mirko S. **Gilardino**, MD, MSc[1,2]; Yichen **Wu**[3]; Sean D. **Jeffries**, BSc[1]; Thomas M. **Hemmerling**, MD, MSc, DEAA[1,4]

1. Department of Experimental Surgery, McGill University Health Center; Montreal, Quebec, Canada.

2. Division of Plastic and Reconstructive Surgery, McGill University Health Center; Montreal, Quebec, Canada.

3. Department of Electrical and Computer Engineering, McGill University; Montreal, Quebec, Canada.

4. Department of Anesthesia, McGill University; Montreal, Quebec, Canada.

Corresponding author:

Thomas M. Hemmerling, MD, MSc, DEAA

Professor, Department of Anesthesiology and Experimental Surgery

McGill University and Montreal General Hospital

1650 Cedar Ave, T8-108

Montreal, Quebec H3G 1A4, Canada

Thomas.Hemmerling@mcgill.ca

The authors have the following to disclose: The research was supported financially by 9330-7353 Qc Inc, and salary support for Robert Harutyunyan was provided via the Mitacs Accelerate grant.

Short Running Head: Novel Web-Based Liposuction System

Abstract

Purpose: Pre-operative planning for liposuction is vital to ensure safe practice and patient satisfaction. However, current standards of fat assessment before surgery are guided by subjective methods such as visual inspection, skin-pinch tests, and waist circumference measurements. This study aimed to develop an inexpensive software-based tool that utilizes ultrasound (US) imaging and an online platform to accurately simulate regional subcutaneous adipose tissue (SAT) distribution and safe volume estimation for liposuction procedures.

Methods: The authors present a web-based platform with integrated 2D and 3D simulations of SAT to support liposuction planning and execution. SAT-Map was constructed using multiple sub-applications linked with the python framework programming language.

Results: The SAT-Map interface provides an intuitive and fluid means of generating patient-specific models and volumetric data. To further accommodate this, an operational manual was prepared to achieve consistent visualization and examination of estimated SAT content. The system currently supports static 2D heatmap simulation and 3D interactive virtual modelling of the SAT distribution. Supplementary clinical studies are needed to evaluate SAT-Map's clinical performance and practicality.

Conclusion:

SAT-Map revolutionizes the concept of pre-operative planning for liposuction by developing the first combined web-based software that objectively simulates fat distribution and measures safe liposuction volume. Our software approach presents a cost-efficient, accessible, and user-friendly system offering multiple advantages over current SAT assessment modalities. The immediacy of clinically accurate 3D virtual simulation provides objective support to surgeons towards improving patient conversation, outcomes, and satisfaction in liposuction procedures.

Introduction

Liposuction is one of the most commonly performed cosmetic procedures in the world.[1,2] In 2021, The Aesthetic Society[3] reported more than 491,000 liposuction procedures performed across the United States alone. First attempted in 1921, the art of liposuction has evolved into one of the most common and safe procedures in plastic surgery, with a complication rate of less than 1% and a mortality rate of approximately 0.02%. [4-7] The wide breadth of liposuction applications spans the fields of aesthetic, reconstructive and functional surgeries. However, it is through its multiple evolutionary instances that liposuction has become the safe and effective technique it is today [8,9]. Some hallmark technical developments included the introduction of suction-assisted lipectomy (SAL), ultrasound-assisted lipectomy (UAL), laser-assisted lipectomy (LAL) and most recently, power-assisted lipectomy (PAL).[10-13]

In tandem with these new techniques, surgeons sought the importance of setting realistic and healthy expectations for the success of any cosmetic procedure.[14] On the one hand, evidence-based pre-operative counselling, including a commitment to a healthy diet and active lifestyle, improved short-term patient satisfaction.[15] Similarly, in several studies[16,17] evaluating long-term subjective and objective outcomes of liposuction, the authors suggested that patient satisfaction rates and recommendations remained high when positive dietary and activity lifestyle habits were maintained. On the other hand, a 25-year review[18] of various liposuction techniques revealed similar overall patient satisfaction regardless of surgical approaches and averaged 82%. Therefore, irrespective of the method employed, pre-operative planning and patient discussion is vital to ensure a high degree of satisfaction. Focusing on the surgical approach, current standards of fat assessment before surgery are guided by visual inspection, skin-pinch tests and waist circumference measurements, all subjective methods.[19] This starkly contrasts with the 3D breast imaging commonly performed before mammoplasty. Systems such as the Vectra 3D (Canfield Scientific, Parsippany, USA) have been more routinely used to pre-operatively plan, simulate realistic postoperative expectations and assess breast implant volume, shape and symmetry with great success compared to 2D measurements.[20,21] On the downside, such tools do not provide a cost-efficient approach.

Taking this into account, the objective of this study was to develop an inexpensive software-based tool that utilizes ultrasound (US) imaging and an online platform to provide an accurate simulation of regional subcutaneous adipose tissue (SAT) distribution and safe volume estimation for liposuction procedures. A companion tool, SAT-Map, was developed to support surgeons with objective and visual guidance prior to liposuction surgery. Accordingly, we addressed the following critical elements: 1) a user-friendly and cost-efficient surgical planning web interface, 2) pre-operative 2D and 3D fat distribution simulation, and 3) estimation of a safe regional liposuction volume.

Methods

System Specifications

SAT-Map is an online dashboard comprising multiple components using the python framework programming language (v.3.9.9, Python Software Foundation, Delaware, USA). Several sub-applications were used with the Python software to develop and manage SAT-Map. Git-Hub (Microsoft Corporation, San Francisco, USA) is a software development hosting platform where source code can be easily managed in the cloud. Next, an integrated development environment (IDE) known as PyCharm (v.2021.3, JetBrains, Prague, Czech Republic) was employed, which provides additional features such as code analysis, debugger functions and version control, amongst others. To provide two-dimensional (2D) and three-dimensional (3D) visualization tools into our online tool, an integrated Python framework-based application known as Dash (v.2.3.1, Plotly, Montreal, Canada) was employed. Using Dash components and graphical libraries from its parent company Plotly (v.5.50, Montreal, Canada), 2D and 3D figures can be created and manipulated in an online dashboard. To host all the above components and any created functions, Heroku (Salesforce, San Francisco, USA), a website hosting platform, was used to deploy SAT-Map online. All the above sub-applications and their functions are summarized in Table 1. Additionally, Figure 1 presents all libraries or modules and their versions employed for SAT-Map construction. The system dashboard was divided into two major parts: the frontend and backend. The frontend defines the app layout and mainly uses Hypertext Markup Language (HTML) modules to set up different visual components of the dashboard. On the other hand, the backend links the frontend components to the '@app. callback' functions for integrated functionality of the various incorporated web elements.

Results

SAT-Map Interface

The SAT-Map interface was constructed to provide an intuitive and fluid means of generating patient-specific graphical figures and volumetric data. To further accommodate this, an operational manual was prepared to attain consistent visualization and examination of estimated SAT content. The system currently supports static 2D heatmap simulation and 3D virtual modelling of the SAT distribution.

Scan Location

The study area that will undergo liposuction must be well established for every patient. The first step is to delineate the operative borders. This can be performed via operative border drawing or other preferential methods. Once complete, patient information can be entered into the first column in SAT-Map's dashboard. Figure 2 presents the landing page for SAT-Map. The blank page shows the option to enter data for a new patient (name, gender, height, and weight) with a randomized identification code for anonymity if desired. Once patient information and specific liposuction-based operation width and length are entered, a specific region can be entered on the scan location section (e.g., Abdomen Crest).

Ultrasound Measurements Protocol

All scans begin at the superior position and follow a pre-set numbering pattern to ensure consistent measurements (Figure 3). It is suggested to refer to the image attached to the scan location for the default ultrasound scanning protocol, either in the vertical or horizontal path (Figure 4). Current protocol standards are to take eight US scans to ensure good proportional distribution to the total anatomical area undergoing liposuction. The appropriate distribution is determined with a ruler as the superficial area (L x W) and divided into equidistant sections. The center of each segment is then approximated for each region. The system supports any even number of subdivisions (e.g., 2,4,6,8 etc.) to accommodate desired accuracy and variable body morphologies. Ultrasound data can now be entered. The simulations assume an equal thickness of SAT and skin in each segment. To avoid skin-related complications, a fat safety assumption rule was established and set at a standard of 1cm, considered a conservative, safe depth from the dermis. This can be modified in 0.25cm increments for operations such as neck liposuction, where fat volumes are significantly reduced. Fat depth is determined by the initial fat/skin intersection and ends at the fat/muscular junction (Figure 5). All depth values are interpreted in centimetres. This can be recorded using the built-in US depth measurement tool followed by manual recording into SAT-Map. Another option is inputting the saved images into SAT-Map's automatic fat depth calculation algorithm for complete automated analysis. This prototype uses an in-house constructed deep learning-based algorithm that automatically extracts fat depths from ultrasound images (Figure 6). However, this model is still under development and has not yet been evaluated for clinical application.

Graphical Representation and Volume Analysis

The final output from the web interface is the representation of a 2D and 3D heatmap displaying regional fat distribution and volume (Figure 6). Specifically, a 2D plane view of the fat distribution will be presented with varying shades of beige and red, where darker shades represent deeper depths. Moreover, the 3D complement is an interactive heatmap which displays the skin (cyan), fat safety assumption region (yellow) and the underlying fat depths (varying shades of red). Figure 7 presents the various orientations of the fat profiles and the associated depth bar chart.

Discussion

Surgical success, minimizing complications and patient satisfaction are fundamental elements of any invasive operation. In plastic surgery, aesthetics is paramount as most results are visible to the patient. Therefore, to optimize excellent results, pre-operative planning is critical. However, current standards in fat transfer procedures involve subjective interpretation of the underlying adipose tissue. This is partly due to imaging techniques such as Magnetic Resonance Imaging (MRI), Computed Tomography (CT) or 3D plastic surgery simulators being costly, time-consuming, and not readily available. The authors successfully created a user-friendly web-based visualization system, which presents fat distribution and the underlying volume (Figure 7). In addition, SAT-Map is designed to calculate the safe amount of regional SAT volume and display the distribution in a heat map-like manner. The software contains a 3D interactive simulation of the underlying morphology. The user can manipulate the model to comprehensively interpret the structural distribution, offering a practical visual guide for surgical planning.

Emerging computer-based technologies for surgical applications have greatly enhanced pre-operative conversation, planning and execution [22]. In the context of conventional liposuction, few computer or web-based platforms have been effectively implemented to date. Such systems' employment is often impeded due to high costs, limited availability and intensive learning curves [23]. Our software approach, SAT-Map, has several significant advantages over traditional imaging solutions for SAT assessment. MRI and CT provide objective data but are complex to interpret and involve a time-consuming procedure compared to ultrasound technology [24]. Plastic surgeons have increasingly implemented ultrasound in their practice [25]. However, given its operator-dependent nature, it is a modality with a significant learning curve for novice users [26]. Therefore, the authors are developing an automated system to monitor appropriate probe pressure for future studies where experts and non-experts may achieve standardized results from ultrasound scans for SAT assessment. Otherwise, the US is practical compared to other imaging modalities for delivering an objective and clinically accurate simulation of the underlying soft tissues. SAT-Map was designed as a web-based platform easily accessible from any smart device or computer to facilitate access and availability, eliminating the need for installing expensive workstations or computer-intensive programs. Moreover, the platform involves no complex manipulations specifically designed for a short learning curve and user-friendly experience.

One of the main features of SAT-Map is the 1cm safety margin (denoted in yellow in Figure 7). This feature is central to the practicality of our system in surgical applications. It was created to consider the volume of adipose tissue untouched during liposuction. Specifically, the apical and fat mantle layers directly adjacent to the dermis [27]. The apical layer resides below the reticular dermis and is surrounded by sweat glands and hair follicles, whereas the mantle layer of fat has a fundamental role in protecting and insulating [28]. It is recommended to avoid disrupting these anatomical elements during traditional liposuction as they can lead to complications [29]. In practice, plastic surgeons leave an approximate 1 cm gap below the dermis to avoid neural, vascular, and lymphatic damage, prevent skin necrosis, and ensure proper recovery after the procedure [28,30]. Therefore, particular importance was placed on implementing the fat safety assumption (FSA). Under ultrasound, the mantle fat is indistinguishable from the remaining subcutaneous adipose tissue (deep fat layer); thus, the fat safety assumption rule was created. Although the mantle layer thickness is not uniform across the body, it is, in fact, relatively uniform in any given area [27]. This allows the FSA rule to operate under a consistent assumption in any anatomical region (i.e., abdomen, thighs, buttocks). In areas with little fat, such as the face or neck or in surgical cases of superficial liposculpting, the fat safety assumption is modified as contouring techniques are adapted from the traditional liposuction [31-34].

In a nationwide survey of factors influencing patient satisfaction in plastic surgery, which were best correlated with the 'likelihood to recommend practice' or 'provider' was the patient's confidence in the care provider and the provider's concern for questions [35]. This study expresses the importance of pre-operative factors in patient satisfaction, retention, and willingness to recommend a given plastic surgeon. Liposuction is often a recurrent body contouring procedure where patients return for different areas or corrective revisions. Therefore, patient satisfaction with the initial procedure is essential. However, measuring the success of liposuction is a very subjective process. Consequently, providing a cost-effective means to guide patient expectations objectively and visually with pre-operative fat estimations can be quite valuable. The SAT-Map system would supply the necessary fat thickness, distribution, symmetry, and regional volume information. In turn, it supports conversation about safe fat removal and mitigating complications such as skin rippling or dimples. Klassen et al. specified that overall satisfaction from participants depended on achieving a firm and symmetric contour [36]. One would therefore assume that our system can contribute to the patient's satisfaction in addition to their willingness to recommend and return to a given surgeon.

Limitations and future direction

The graphical representation of adipose tissue is the main limiting factor in our software. To further improve our model, the development of a verisimilitude design that is geometrically lifelike is crucial. In this manner, the 3D models would resemble realistic patient morphology and could be overlaid with real patient images. Such a feat would facilitate the generation of patient-specific care supported by clinically accurate SAT estimates with natural contours for pre-operative planning. Second, to promote greater accessibility, the software should be converted into an application available on all smart devices. Lastly, clinical studies are needed for validating SAT-Map in the following categories: SAT estimation accuracy, realism, and usability.

Conclusion

SAT-Map revolutionizes the concept of pre-operative planning for liposuction by developing the first combined web-based software that objectively simulates fat distribution and measures safe liposuction volume. Our software approach presents a cost-efficient, accessible, and user-friendly system offering multiple advantages over current SAT assessment modalities. The immediacy of clinically accurate 3D virtual simulation provides objective support to surgeons towards improving patient conversation, outcomes, and satisfaction in liposuction procedures. Future work will focus on developing verisimilitude models and further validating SAT-Map's accuracy and applicability to fat-based procedures.

References

1. Dolsky RL, Newman J, Fetzek JR, Anderson RW. Liposuction. History, techniques, and complications. Dermatol Clin. 1987;5(2):313-333.

2. Bellini E, Grieco MP, Raposio E. A journey through liposuction and liposculture: Review. Annals of Medicine and Surgery. 2017;24:53-60.

3. Aesthetic plastic surgery national databank statistics 2020–2021. Aesthetic Surgery Journal. 2022;42(Supplement_1):1-18.

4. Sterodimas A, Boriani F, Magarakis E, Nicaretta B, Pereira L, Illouz Y. Thirtyfour years of liposuction: past, present and future. Eur Rev Med Pharmacol Sci. 2012;16(3):393-406.

5. Housman TS, Lawrence N, Mellen BG, et al. The safety of liposuction: results of a national survey. Dermatologic surgery. 2002;28(11):971-978.

6. Hanke CW, Bernstein G, Bullock S. Safety of tumescent liposuction in 15,336 patients: National survey results. Dermatologic surgery. 1995;21(5):459-462.

7. Mendez BM, Coleman JE, Kenkel JM. Optimizing patient outcomes and safety with liposuction. Aesthetic Surgery Journal. 2018;39(1):66-82.

8. Halk AB, Habbema L, Genders RE, Hanke CW. Safety studies in the field of liposuction: A systematic review. Dermatologic Surgery. 2019;45(2):171-182.

9. Chia CT, Theodorou SJ. 1,000 consecutive cases of laser-assisted liposuction and suction-assisted lipectomy managed with local anesthesia. Aesthetic Plastic Surgery. 2012;36(4):795-802.

10. Apesos J, Chami R. Functional applications of suction-assisted lipectomy: A new treatment for old disorders. Aesthetic Plastic Surgery. 1991;15(1):73-79.

11. Maxwell PG, Gingrass MK. Ultrasound-assisted lipoplasty: A clinical study of 250 consecutive patients. Plastic and Reconstructive Surgery. 1998;101(1):189-202.

12. Zelickson BD, Dressel TD. Discussion of laser-assisted liposuction. Lasers in Surgery and Medicine. 2009;41(10):709-713.

13. Mann MW, Palm MD, Sengelmann RD. New advances in liposuction technology. WB Saunders; 2008:72-82.

14. Crockett RJ, Pruzinsky T, Persing JA. The influence of plastic surgery “reality tv” on cosmetic surgery patient expectations and decision making. Plastic and Reconstructive Surgery. 2007;120(1):316-324.

15. Rohrich RJ, Broughton GI, Horton B, Lipschitz A, Kenkel JM, Brown SA. The key to long-term success in liposuction: A guide for plastic surgeons and patients. Plastic and Reconstructive Surgery. 2004;114(7):1945-1952.

16. Masoumi Lari SJ, Roustaei N, Roshan SK, Chalian M, Chalian H, Honarbakhsh Y. Determinants of patient satisfaction with ultrasound-assisted liposuction. Aesthetic Surgery Journal. 2010;30(5):714-719.

17. Lipp MB, Butterwick K, Angra K, Chunhara C, Goldman MP. Evaluation of long-term outcome and patient satisfaction results after tumescent liposuction. Dermatologic Surgery. 2020;46:S31-S37.

18. Triana L, Triana C, Barbato C, Zambrano M. Liposuction: 25 years of experience in 26,259 patients using different devices. Aesthetic Surgery Journal. 2009;29(6):509-512.

19. Azzi AJ, Lafreniere AS, Viezel-Mathieu A, Hemmerling TM, Gilardino M. Objective quantification of liposuction results. J Cutan Aesthet Surg. 2018;11(3):105-109.

20. Wood KL, Zoghbi Y, Margulies IG, Ashikari AY, Jacobs J, Salzberg CA. Is the vectra 3d imaging system a reliable tool for predicting breast mass? Annals of Plastic Surgery. 2020;85(S1):S109-S113.

21. Bai L, Lundström O, Johansson H, et al. Clinical assessment of breast symmetry and aesthetic outcome: can 3D imaging be the gold standard? Journal of Plastic Surgery and Hand Surgery. 2022:1-8.

22. Kayastha D, Vakharia KT. The evolving roles of computer-based technology and smartphone applications in facial plastic surgery. Current Opinion in Otolaryngology & Head and Neck Surgery. 2019;27(4):267-273.

23. Schendel SA, Montgomery K. A web-based, integrated simulation system for craniofacial surgical planning. Plastic and Reconstructive Surgery. 2009;123(3):1099-1106.

24. Azzi AJ, Lafrenière AS, Gilardino M, Hemmerling T. Ultrasonography technique in abdominal subcutaneous adipose tissue measurement: A systematic review. J Ultrasound Med. 2019;38(4):877-888.

25. Swanson E. The expanding role of diagnostic ultrasound in plastic surgery. Plastic and reconstructive surgery Global open. 2018;6(9):e1911-e1911.

26. Mullaney PJ. Qualitative ultrasound training: defining the learning curve. Clinical Radiology. 2019;74(4):327.e7-327.e19.

27. Klein JA. Tumescent technique: tumescent anesthesia & microcannular liposuction. Mosby Incorporated; 2000.

28. Kaminski MV, Lopez de Vaughan RM. The anatomy and physiology metabolism/nutrition of subcutaneous fat. In: Shiffman MA, Di Giuseppe A, eds. *Liposuction: Principles and Practice*. Springer Berlin Heidelberg; 2006:17-25.

29. Kim YH, Cha SM, Naidu S, Hwang WJ. Analysis of postoperative complications for superficial liposuction: A review of 2398 cases. Plastic and Reconstructive Surgery. 2011;127(2):863-871.

30. Thomas M, D'silva J, Abraham A. Use of technologies to improve the liposuction outcome including skin texture and form. *Enhanced Liposuction-New Perspectives and Techniques*. IntechOpen; 2021.

31. Illouz YG. Illouz's technique of body contouring by lipolysis. Clin Plast Surg. 1984;11(3):409-17.

32. Gasperoni C, Gasperoni P. Subdermal liposuction: long-term experience. Clin Plast Surg. 2006;33(1):63-73, vi.

33. Saad A, Combina LN, Altamirano-Arcos C. Abdominal etching. Clin Plast Surg. 2020;47(3):397-408.

34. Saad AN, Pablo Arbelaez J, De Benito J. High definition liposculpture in male patients using reciprocating power-assisted liposuction technology: Techniques and results in a prospective study. Aesthetic Surgery Journal. 2019;40(3):299-307.

35. Chen K, Congiusta S, Nash IS, et al. Factors influencing patient satisfaction in plastic surgery: A nationwide analysis. Plastic and Reconstructive Surgery. 2018;142(3):820-825.

36. Klassen AF, Cano SJ, Scott A, Johnson J, Pusic AL. Satisfaction and quality-of-life issues in body contouring surgery patients: A qualitative study. Obesity Surgery. 2012;22(10):1527-1534.

37. Woman torso in underwear with medical marks for plastic surgery or liposuction. Accessed Septemeber 2nd, 2021. Envato Elements Pty Ltd

Tables:

Table 1. Description of programming language and sub-applications used to build the SAT-Map dashboard.

Name	Function
Python (v.3.9.9)	High level programming language with dynamic semantics.
GitHub	Cloud-based code hosting platform.
PyCharm (v.2021.3)	Python integrated development environment.
Plotly (v.5.5.0)	Library for data science models and charts.
Dash (v.2.3.1)	Framework for building data visualisation interfaces.
Heroku	Platform as a service (PaaS) for running applications entirely in the cloud.

Figures Legend:

Figure 1. List of libraries and modules used in the development of the SAT-Map dashboard.

Figure 2. The landing page for SAT-Map where patient information, study area and measurement details can be filled out before fat volume and distribution estimation.

Figure 3. Examples of horizontal and vertical matrix-style numbering necessary for consistent scanning protocol during ultrasound-based measurements (abdominal crest and thighs shown).

Figure 4. An example of the SAT-Map page when patient information, measurement, and scan location entries are filled and ready for ultrasound information to be entered next.

Figure 5. Depiction of the dermis, subcutaneous adipose tissue, muscle fascia and muscle layers in an ultrasound scan.

Figure 6. Complete SAT-Map dashboard prototype with final 2D heatmap and 3D simulation shown and constructed from the integrated ultrasound images.

Figure 7. SAT-Map generated fat profile from 8 randomized US scans in a hypothetical thigh liposuction case. A) Two-dimensional heatmap of underlying SAT depth. B) Three-dimensional deep to a superficial view of SAT depth. C) Three-dimensional anterior view of the inner thigh. D) Three-dimensional diagonal view of the inner thigh. The numbering pattern is synonymous with the inner thigh image depicted in 'scan location' in Figure 2. The cyan colour describes skin, and the yellow colour defines the fat safety region (also known as the 1cm fat safety assumption). Shades of beige and red signify operable fat for liposuction. Lighter to darker shades represent increasing depth, as displayed on the bar chart of each figure.

Figures:

Figure 1. List of libraries and modules used in the development of the SAT-Map dashboard.

- absl-py==1.0.0
- appnope==0.1.2
- astunparse==1.6.3
- attrs==21.4.0
- backcall==0.2.0
- Brotli==1.0.9
- cachetools==4.2.4
- certifi==2021.10.8
- charset-normalizer==2.0.10
- click==8.0.3
- cycler==0.11.0
- dash==2.3.1
- dash-bootstrap-components==1.0.2
- dash-core-components==2.0.0
- dash-html-components==2.0.0
- dash-table==5.0.0
- decorator==5.1.0
- distlib==0.3.4
- filelock==3.6.0
- Flask==2.0.2
- Flask-Compress==1.10.1
- flatbuffers==2.0
- fonttools==4.28.5
- gast==0.4.0
- google-auth==2.3.3
- google-auth-oauthlib==0.4.6
- google-pasta==0.2.0
- grpcio==1.43.0
- gunicorn==20.1.0
- h5py==3.6.0
- idna==3.3
- imageio==2.13.5
- imagezmq==1.1.1
- importlib-metadata==4.10.1
- imutils==0.5.4
- iniconfig==1.1.1
- ipython==7.30.1
- iteration-utilities==0.11.0
- itsdangerous==2.0.1
- jedi==0.18.1
- Jinja2==3.0.3
- joblib==1.1.0
- keras==2.8.0rc0
- Keras-Preprocessing==1.1.2
- kiwisolver==1.3.2
- libclang==12.0.0
- Markdown==3.3.6
- MarkupSafe==2.0.1
- matplotlib==3.5.1
- matplotlib-inline==0.1.3
- networkx==2.6.3
- numpy==1.22.0
- oauthlib==3.1.1
- opencv-contrib-python==4.5.5.62
- opencv-python==4.5.5.62
- opt-einsum==3.3.0
- packaging==21.3
- pandas==1.3.5
- parso==0.8.3
- pexpect==4.8.0
- pickleshare==0.7.5
- Pillow==9.0.0
- platformdirs==2.5.2
- plotly==5.5.0
- pluggy==1.0.0
- prompt-toolkit==3.0.24
- protobuf==3.19.3
- ptyprocess==0.7.0
- py==1.11.0
- pyasn1==0.4.8
- pyasn1-modules==0.2.8
- pycurl==7.45.1
- Pygments==2.11.1
- pyparsing==3.0.6
- pytest==7.1.1
- python-dateutil==2.8.2
- pytz==2021.3
- PyWavelets==1.2.0
- pyzmq==22.3.0
- requests==2.27.1
- requests-oauthlib==1.3.0
- rsa==4.8
- scikit-image==0.19.1
- scikit-learn==1.0.2
- scipy==1.7.3
- six==1.16.0
- tabulate==0.8.9
- tenacity==8.0.1
- tensorboard==2.8.0
- tensorboard-data-server==0.6.1
- tensorboard-plugin-wit==1.8.1
- tensorflow==2.8.0
- tensorflow-estimator==2.7.0
- tensorflow-io-gcs-filesystem==0.23.1
- termcolor==1.1.0
- threadpoolctl==3.0.0
- tifffile==2021.11.2
- tomli==2.0.1
- traitlets==5.1.1
- typing_extensions==4.0.1
- urllib3==1.26.8
- virtualenv==20.14.1
- wcwidth==0.2.5
- Werkzeug @ https://github.com/pallets/werkzeug/archive/refs/tags/2.0.1.tar.gz
- wrapt==1.13.3
- zipp==3.7.0

Module/Library name==Version Number.

Figure 2. The landing page for SAT-Map where patient information, study area and measurement details can be filled out before fat volume and distribution estimation.

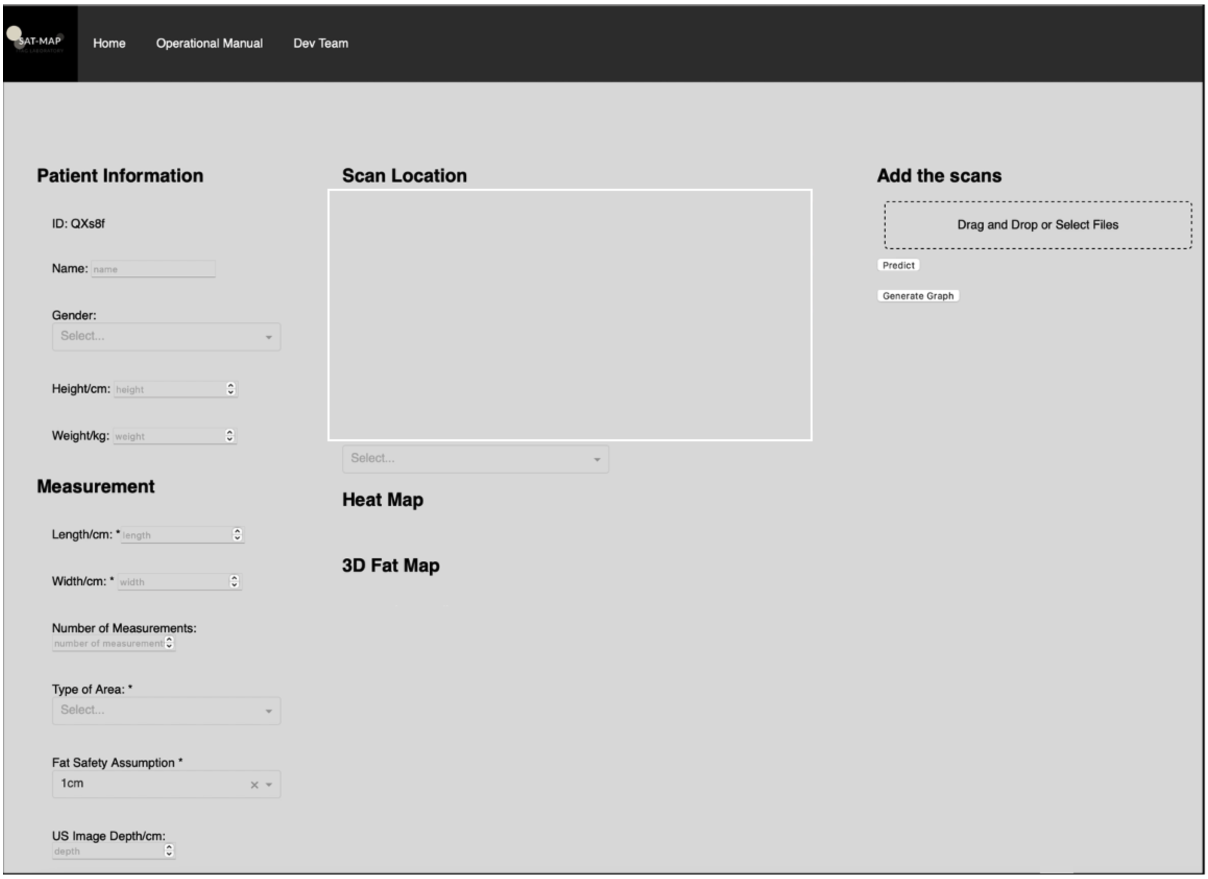
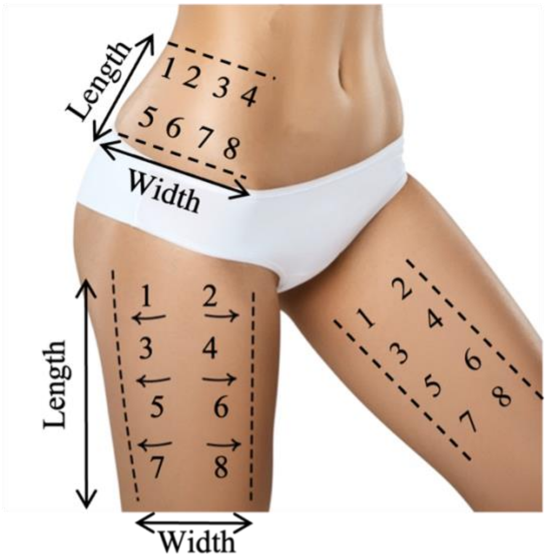


Figure 3. Examples of horizontal and vertical matrix-style numbering necessary for consistent scanning protocol during ultrasound-based measurements (abdominal crest and thighs shown).



Adapted from Envato Elements.[37]

Figure 4. An example of the SAT-Map dashboard when patient information, measurement, and scan location entries are filled and ready for ultrasound information to be entered next.

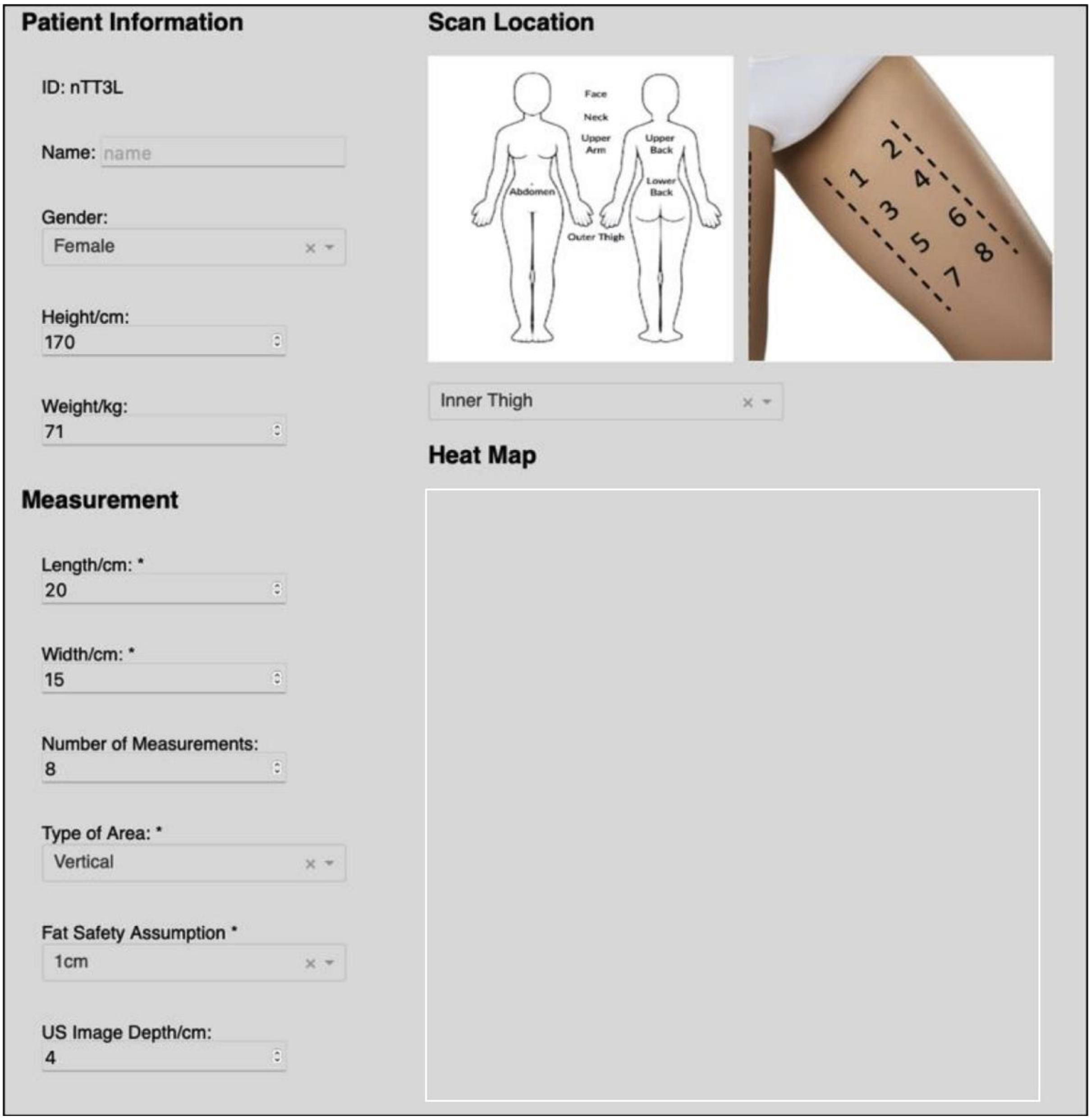


Figure 5. Depiction of the dermis, subcutaneous adipose tissue, muscle fascia and muscle layers in an ultrasound scan.

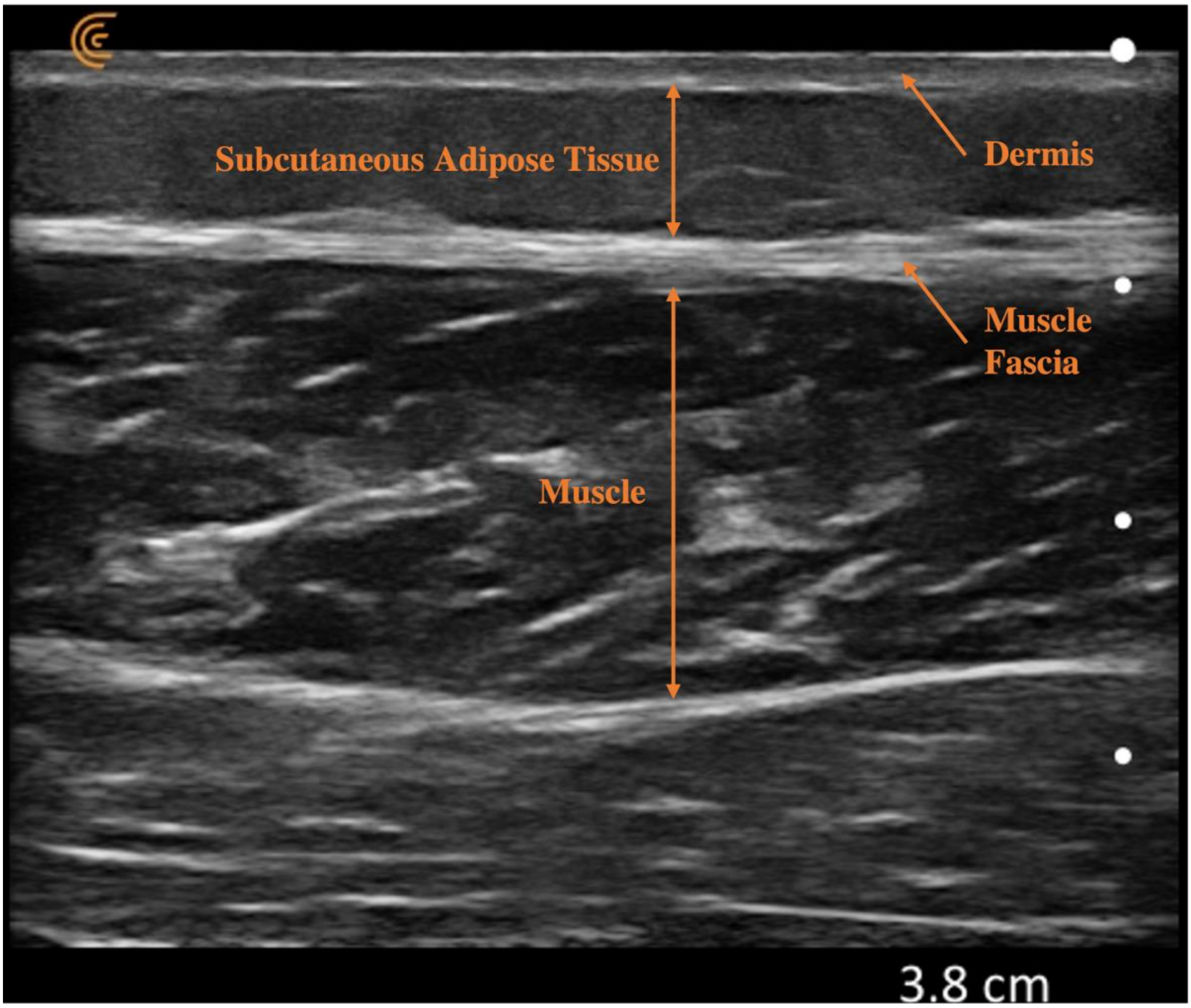


Figure 6. Complete SAT-Map dashboard prototype with final 2D heatmap and 3D simulation shown and constructed from the integrated ultrasound images.

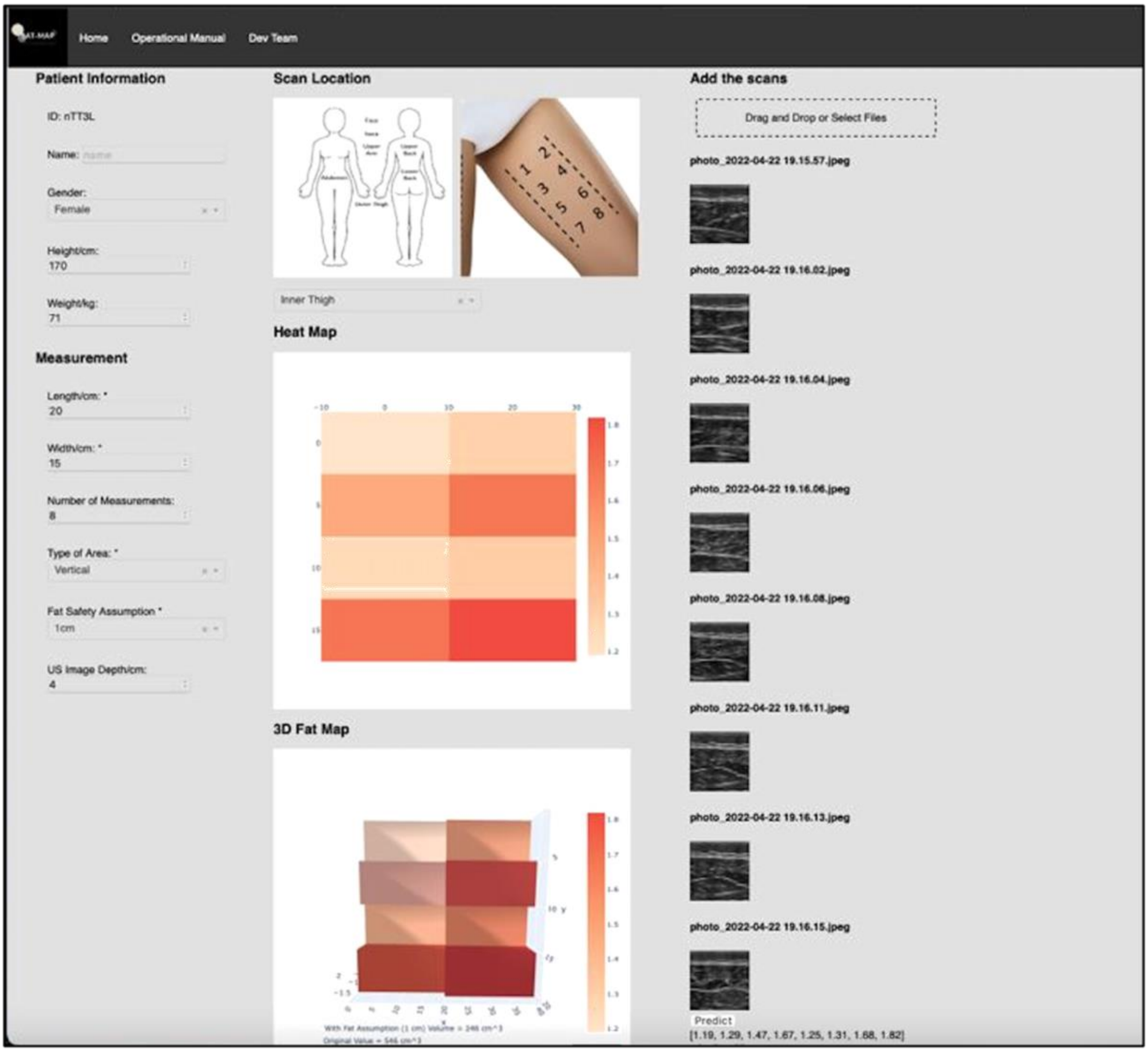
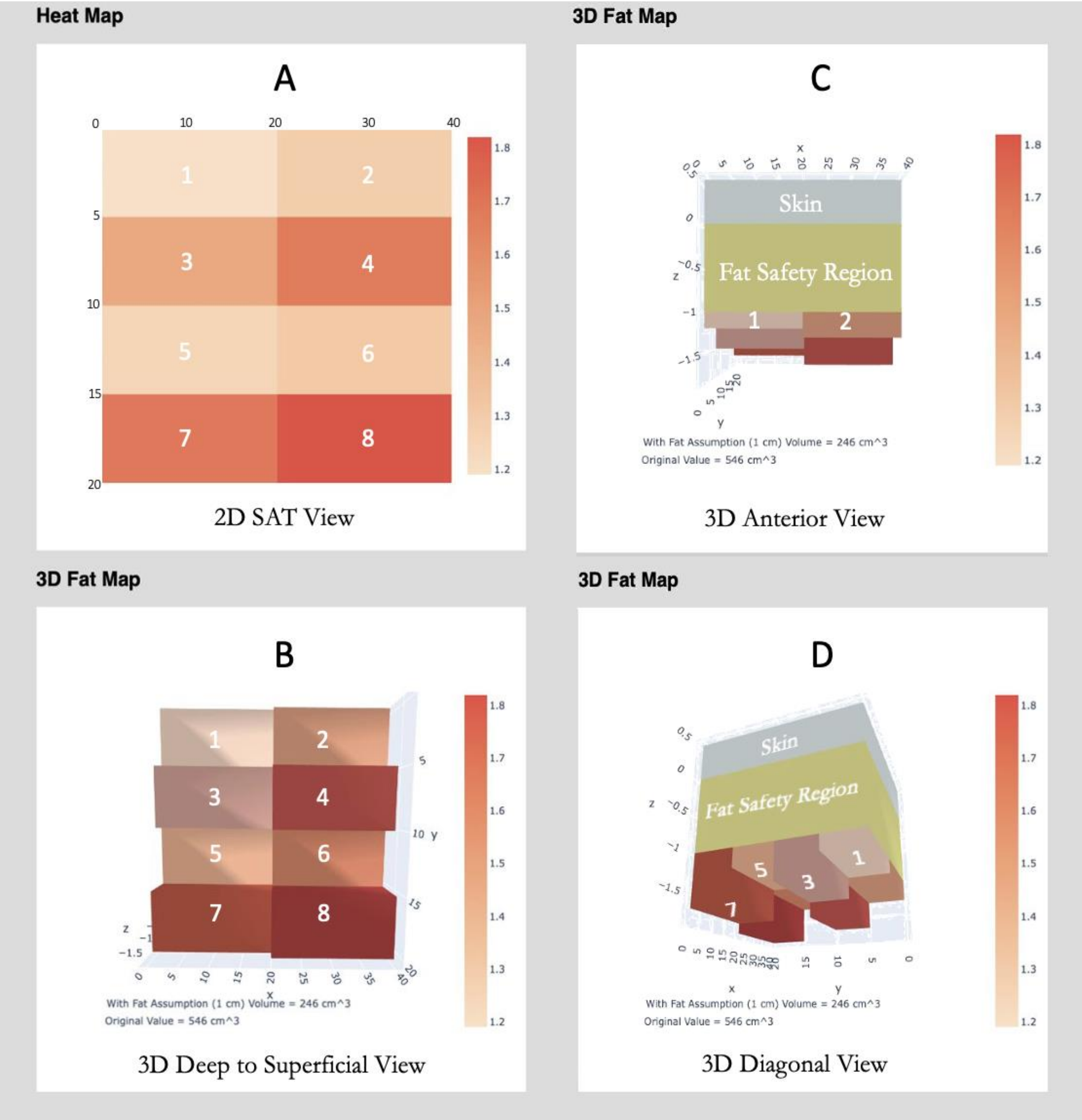


Figure 7. SAT-Map generated fat profile from 8 randomized US scans in a hypothetical thigh liposuction case. A) Two-dimensional heatmap of underlying SAT depth. B) Three-dimensional deep to a superficial view of SAT depth. C) Three-dimensional anterior view of the inner thigh. D) Three-dimensional diagonal view of the inner thigh. The numbering pattern is synonymous with the inner thigh image depicted in 'scan location' in Figure 2. The cyan colour describes skin, and the yellow colour defines the fat safety region (also known as the 1cm fat safety assumption). Shades of beige and red signify operable fat for liposuction. Lighter to darker shades represent increasing depth, as displayed on the bar chart of each figure.



Bridging text

Technology has had a transformative impact in the realm of surgery with advances in computer-assisted technologies that utilize augmented and virtual reality, robotics and 3D printing, to name a few. In chapter 2, the article describing the novel software SAT-Map presented the potential such technologies can have in the division of plastic and reconstructive surgery. Appreciating the importance of adipose tissue within the field, yet understanding its subjective management, the construction of SAT-Map is the first step toward bridging this gap. Predominantly, the ability to pre-operatively simulate and quantify SAT in a safe and effective approach.

Following the technical description of SAT-Map, evidence-based studies were necessary to ascertain the validity and feasibility of the software as a tangible quantitative tool. Therefore, the next chapter will investigate the agreement between dry liposuction aspirate measurements and ultrasound estimations from SAT-Map in the context of a pilot trial in liposuction patients. Intra-operative aspirated adipose tissue volume can be easily recorded after gravity separation (routinely performed) and directly compared with ultrasound estimates from SAT-Map. Lipoplasty canisters have precise graduation in which aspirate volumes can be accurately measured. Furthermore, liposuction was chosen as the procedure of choice, given its high frequency in private practice and wide anatomical application. The combination provides an excellent framework for testing software accuracy and feasibility in a high-volume center. In the grand scheme, collecting a greater yield of data allows the development of more precise protocols, which may translate more effectively to other fat transfer-based procedures in the future.

Chapter 3 – Article 2

Ultrasound Calculation of Fat Volume Before Liposuction: A New Method

Author list: Robert **Harutyunyan**, BSc[1]; Mirko S. **Gilardino**, MD, MSc[1,2]; Vasilios W. **Papanastasiou**, MD, MSc [2]; Thomas M. **Hemmerling**, MD, MSc, DEAA[1,3]

1. Department of Experimental Surgery, McGill University Health Center; Montreal, Quebec, Canada.

2. Division of Plastic and Reconstructive Surgery, McGill University Health Center; Montreal, Quebec, Canada.

3. Department of Anesthesia, McGill University; Montreal, Quebec, Canada.

Corresponding author:

Thomas M. Hemmerling, MD, MSc, DEAA

Professor, Department of Anesthesiology and Experimental Surgery

McGill University and Montreal General Hospital

1650 Cedar Ave, T8-108

Montreal, Quebec H3G 1A4, Canada

Thomas.Hemmerling@mcgill.ca

The authors have the following to disclose: The research was supported financially by 9330-7353 Qc Inc, and salary support for Robert Harutyunyan was provided via the Mitacs Accelerate grant.

Presented at: CSPS 75th Annual Meeting, Quebec City, QC from June 14th to 18th, 2022.

Short Running Head: Ultrasound-Based Fat Volume Calculation

Abstract

Purpose: Fat manipulation procedures, such as liposuction, contain a degree of subjectivity primarily guided by the surgeon's visual or tactile perception of the underlying fat. Currently, no cost-effective and direct method to objectively measure fat depth and volume in real-time. Using innovative ultrasound-based software, the authors aim to validate fat tissue volume and distribution measurements in the pre-operative setting.

Methods: A total of 18 participants were recruited to evaluate the accuracy of the new software. The pilot study conducted trials at a plastic surgery clinic associated with McGill University Health Center. Recruited participants underwent ultrasound scans within the pre-operative markings of the study area before surgery. Ultrasound estimated fat profiles were generated using the in-house software and compared directly with the intra-operative aspirated fat recorded after gravity separation.

Results: Participants' mean age and BMI were 47.6 ± 11.3 years and 25.6 ± 2.3 kg/m^2, respectively. Evaluation of trial data showed promising results following the use of a Bland Altman agreement analysis. For the 18 patients and 44 volumes estimated, 43/44 measurements fall within an agreement of 95% compared to the clinical lipoaspirate (dry) volumes collected post-surgery. The bias was estimated at 9.15 mL with a standard deviation of 17.08 mL and 95 % confidence limits of -24.34 mL and 42.63 mL.

Conclusion: Pre-operative fat assessment measurements agree significantly with intraoperative lipoaspirate volumes. The pilot study demonstrates, for the first time, a novel companion tool with the prospect of supporting surgeons in surgical planning, measuring, and executing the transfer of adipose tissues.

Introduction

Adipose tissue plays a fundamental role in plastic surgery, extending from fat extraction via liposuction to the transfer of vascularized flaps for oncologic and reconstruction purposes following a traumatic injury.[1] Surgeons estimate the required fat volume for operative procedures by visual and tactile perception (i.e., pinch test).[2] This acquired sense dictates procedural behaviour where complications commonly result in body contour irregularities and, in rare cases, potentially lethal pulmonary thromboembolism due to inadvertent violation of the vasculature.[3] Current methods to objectively measure adipose tissue thickness are limited mainly to Magnetic Resonance Imaging (MRI) and Computed Tomography (CT). Although both techniques provide great characterization, they are resource and time-consuming modalities with limited availability.[2] Moreover, CT involves radiation exposure, which can pose an unnecessary health risk. On the one hand, there is a gap in the literature regarding objective measurement procedures that incorporate subcutaneous adipose tissue (SAT) volume in a pre-operative, rapid, and cost-efficient approach. Ultrasound (US), on the other hand, is a well-established, readily available, inexpensive, and radiation-free modality that provides the means necessary to construct an objective pre-operative tool. Multiple studies have validated the effectiveness of US use for fat quantification and have shown excellent agreement with MRI and CT.[4-6] Therefore, the introduction of an inexpensive and objective quantification method of subcutaneous adipose tissue using ultrasound would be of great value.

To that end, the novel in-house software termed SAT-Map was developed. Using ultrasound images, it automatically estimates body fat volume and simulates fat profiles by creating heat map-like visual representations of the SAT distribution. In this pilot study, the authors seek to validate the agreement between pre-operative ultrasound fat estimates and intraoperatively collected lipoaspirate volumes.

Methods

Pilot Study Design and Patient Recruitment:

A total of 18 participants 18 years and older were selected to evaluate the accuracy of the pilot software. The sample size was determined from a recent review of 4534 liposuction patients from the members of the American Society of Plastic Surgeons.[7] Specifically, we assumed a power of 80%, an alpha value of 5%, an estimated mean of 2.14L of lipoaspirate, and a standard deviation of 1.8L (two-tailed test), which yielded 132 participants. Several authors[8,9] recommend that a pilot study sample should be 10% of the projected sample size of the larger parent study. Other sources[10-13] recommend between 10 and 30 participants for the same study design. Thus, this pilot project has recruited 18 participants as indicated above and within the guidelines of previous studies.

The study was conducted at a plastic surgery clinic associated with our academic institution, McGill University Health Center (MUHC), which regularly performs surgical procedures involving adipose tissue in Montreal (QC, Canada). Adult patients were selected based on their procedure of choice, namely if they elected to undergo standard liposuction (suction, power, or ultrasound-assisted) and did not opt for any non-invasive techniques of lipolysis. Additional grounds for exclusion included previous treatments in the study area in which the consistency of fat may have been altered. Participation in the study was independent of the patient's planned procedure or surgical outcome and did not involve any risk. Participants were selected in a nonblinded manner, were informed of the study parameters, and signed a consent form. The study was approved by the institutional review board of McGill University and was conducted following the accepted protocols.

Recruited participants underwent an ultrasound adipose tissue scan within the pre-operative markings of the study area before surgery. Ultrasound measurements were performed using the Portable Sonostar UProbe-L5C linear ultrasound device (Sonostar

Technologies Co., Guangzhou, China) and recorded by an expert operator (TH) preceding liposuction. Intra-operative aspirated adipose tissue volume was recorded after separation (gravity), as is routinely done. Pre-operative ultrasound adipose tissue estimations were compared directly with the intra-operative aspirated fat.

Surrogate Procedure:

Liposuction was chosen as a surrogate procedure for assessing and standardizing fat measurement since ultrasound measurements can readily be correlated with extracted fat volumes. Specifically, lipoplasty canisters with precise graduations are used to measure aspirate volumes effectively. Due to the different densities of fat and the tumescent fluid, aspirated contents will separate naturally. The remaining volume of separated dry fat will be used in this study and termed the true liposuction fat volumes. Additionally, the surgeon can obtain more ultrasound images from the same patient for multiple planned procedures. Increasing the measurements yield provides greater clinical data to evaluate the new method effectively.

Software:

SAT-Map is an in-house developed computer-based application that utilizes ultrasound subcutaneous adipose tissue measurements to generate a 2D and 3D heat map displaying underlying fat volume distribution (Figure 1). SAT-Map is a standalone, online dashboard application incorporating patient information and measurement inputs. All participant data is stored on a secure host device offline. All input data on the web-based dashboard is automatically deleted once the page is refreshed.

Data Collection:

The operating surgeon must determine the operative borders for each procedure before employing the established SAT-Map protocol. Once complete, the length (L) and width (W) of the operative field, which will be used for the basis of SAT-Map's calculations, are recorded. In addition to the volumetric adipose tissue data previously mentioned, general data about the patient, including birth year, sex, height, and weight (BMI), are recorded. All participants were standing during the ultrasound measurements. Scanning protocol begins at the superior positions and follows a pre-set numbering pattern to ensure consistent measurement protocols (Figure 2). Fat depth was defined by the fat/skin intersection until the fat/muscular junction. Depth was recorded in centimetres (cm). Current protocol standards are to take eight US measurements to ensure good proportional distribution to the total area undergoing liposuction.

Two factors must be controlled during data collection: scanning procedure and ultrasound probe technique. First, pre-operative surgical markings are used as guidelines to determine the appropriate proportional distribution of the study area. Figure 1 presents an example of SAT-Map's graphical representation associated with a thigh procedure. As depicted, each rectangular prism represents a single US scan. To achieve these, a few criteria are necessary to estimate volumes consistently. First, the superficial area (L x W) is divided into eight equidistant segments using a ruler. Figure 2 displays an example of a vertical 4x2 matrix (e.g., thigh) created from the numbering pattern. The number of subdivisions can be modified to yield greater accuracy or to accommodate varying surface areas (vertical or horizontal matrices). The operator then approximates the center of each segment and collects the ultrasound scans at the marked location. SAT-Map assumes an even distribution of elements such as skin and fat from the center point to the periphery of each segment. The software will then render all images, extract the fat depths, and automatically generate the SAT distribution and volume profiles using the in-house algorithm.

Secondly, importance is placed on the ultrasound scanning technique to minimize tissue distortion from probe compression. In recent years, plastic surgeons have gradually implemented ultrasound use in their practice.[14] However, due to its learning curve, the authors are developing an automated system to monitor appropriate probe pressure for future studies. In this pilot study, ultrasound scans were manually collected by an expert ultrasound operator (TH) to mitigate this. The operator was independent from all analyses and fat collection procedures. Specific indications were to capture ultrasound images with minimal tissue distortion. Using sufficient coupling gel, the probe was handled as if it was brushing the skin's surface and held perpendicularly to avoid compression and the parallax effect, respectively.[15]

Statistical Analysis:

The statistical analysis was performed using SPSS statistical software version 28 (IBM Corp., Armonk, New York). A comparison of pre-operative adipose tissue measurement with intra-operative aspiration was performed. All data were tested with the Shapiro-Wilk test of normality and the Wilcoxon-signed rank test. A P-value <0.05 was used to determine statistical significance. A test of the agreement was performed in the form of a Bland Altman plot to assess two quantitative measurement methods.[16] The data was evaluated via the agreement between clinical liposuction measures and ultrasound estimates. Specifically, the quantification of the agreement through the mean difference, also known as bias, and limits of agreement at the 95% confidence interval (CI). The statistical limits were constructed by using the mean and the standard deviations of the differences. An estimated agreement interval of 95 % where differences in liposuction results fall were deemed acceptable by the authors based on clinical experience. The use of correlation was not considered appropriate in this study because it measures the relationship between one method and another. The Bland Altman analysis is a suitable method to assess the comparability between the two methods.[17]

Results

In this pilot study, eighteen female participants who were operated on between April 2021 and November 2021 underwent pre-operative ultrasound fat estimation using the novel SAT-Map technique before liposuction. Participants' ages range from 26 to 75 years, with a mean of 47.6 ± 11.3 years. The mean BMI of the sample population was 25.6 ±2.3 kg/m^2. A total of 44 procedures among several anatomical locations were recorded between the 18 participants. The most common liposuction procedure performed was the abdominal flank (crest), comprising 20/44 (45%) of total surgical operations. The complete baseline characteristics are presented in Table 1 below.

Direct comparisons of clinical liposuction results and SAT-Map volume estimates, absolute difference, and results differences are presented for all 18 participants and 44 procedures in Table 2. Average volumes of both techniques were found to be 214 mL for true volumes and 223 mL for ultrasound estimates, with a standard deviation of the difference between the means of 28.47 (Figure 3). The Wilcoxon signed-rank test statistic revealed that the measures differed significantly, with a z-score of -3.45 and a p-value of <0.05. The mean percent result difference was calculated at 94% between true and estimated volumes (100% is defined as no difference between techniques). The pre-operative adipose tissue measurement was directly compared with the intra-operative aspiration volumes. Figure 4 illustrates a Bland Altman plot used to evaluate the agreement between SAT-Map estimations and true lipoaspirate volumes (reference standard). This method provides identification of any systematic difference between the measurements or possible outliers. The mean value is zero when two methods agree, indicating no difference. The bias was found to be 9.15 mL with a standard deviation of 17.08 mL and confidence limits of -24.34 mL and 42.63 mL. For the 18 patients and 44 data points collected, 43 of 44 measurements fall within an agreement of 95% CI compared to the reference standard.

Discussion

In plastic surgery and liposuction specifically, operations are typically conducted with a sense of a subjective visual and tactile perception of the underlying fat distribution. Although CT and MRI have been shown to measure SAT thickness successfully, these modalities are both resource and time-consuming.[18,19] Moreover, CT carries an additional associated risk of radiation exposure. Thus, SAT-Map, a novel combination of software and imaging technique, is proposed alongside a cost-effective, time-efficient, and dynamic imaging modality in the traditional hand-held ultrasound. The authors conducted a pilot validation study of the novel companion tool with 18 participants and 44 fat volumes collected and achieved an encouraging agreement between the methods indicated by a bias of 9.15 mL and 95% CI of -24.34 and 42.63.

This study follows suit of a recent systematic review[2] which described that a paucity of work had explored objective measurement of adipose tissue thickness and even fewer for volumetric assessments in the context of the traditional surgical liposuction. The excellent characterization of MRI, CT and US makes them powerful modalities for assessing soft tissues such as SAT. Hernandez et al.,[20] published an MRI study evaluating volumetrically visceral and subcutaneous adipose tissue before and after lipectomy. Similarly, Benatti et al.,[21] have shown in their research that CT is an effective technique for measuring body fat distribution before and after liposuction. The same is true for the US; Bilgili et al.,[22] have indicated that the US is a valuable tool for quantitatively assessing SAT thickness intended to evaluate liposuction results. In sum, the above studies present the potential for these techniques as diagnostic aids for SAT assessment. However, implementing accurate US volume estimations has not been effectively translated into a clinical approach in aesthetic surgery. To the authors' knowledge, no published work has presented a novel software that simultaneously provides a graphical distribution and volumetric estimation of SAT across a target area. SAT-Map is implementing an effective US-based strategy to deliver objective pre-operative planning and execution of fat transfer during liposuction.

In the context of liposuction procedures, where volumes can reach above 5000mL in bariatric or large volume liposuction cases, this study averaged a significantly smaller mean overall aspirate volume of 214mL (Figure 3).[23,24] On the other hand, the estimated volumes were calculated at 223 mL, indicating an average difference of 9 mL. The gradation accuracy observed from liposuction canisters is often estimated at the nearest 10mL, 50mL, 100mL or larger gradation, depending on the model and size.[25] Given this precision, it is believed that the estimates from SAT-Map fall within a safe and accurate range from the actual volumes. This, in turn, provides confidence in the safety and applicability of SAT-Map for future fat transfer-based procedures.

Assessing novel medical techniques to an established one is a common task as new methods and devices are constantly being developed across medical specialties. However, the comparison of new clinical measurement techniques is not trivial. Correlation coefficients are often used for such assessments where the data can often be misleading.[16] The Bland Altman analysis is a reliable approach to determine whether the difference between the techniques or devices is within acceptable limits of agreement.[17] Figure 4 presents the agreement between SAT-Map estimations and true lipoaspirate volumes, where 43 of 44 data points fall within an agreement of 95% CI. The outlier is considered a significant error and is believed to be caused by overestimating the surgical boundaries during pre-operative planning. It is thought that the liposuction procedure was performed on a wider area than initially planned which yielded the discrepancy in the plot. Moreover, the plot may indicate a greater agreement at smaller volumes (<300mL) when comparing data over the volume spectrum. However, a supplementary study is needed to determine widespread liposuction use and fully ascertain the variability of results as volumes increase. Still, the authors have deemed that the current most significant variances (excluding the outlier) are minor enough for small-scale liposuction use on ideal patients such as those from this study (Mean BMI of 25.6 kg/m^2). The current recommendations are that ideal liposuction candidates have a stable body weight within 20-30% of the normal BMI.[26] The results certify that ultrasound estimation using SAT-Map is a technique worth investigating further for aesthetic surgical applications.

Several limitations and factors must be addressed when assessing the novel technique. Firstly, the degrees of body tissue distortion due to compression during ultrasound operation depends on operator force and can misrepresent adipose volume. Improper probe technique can lead to the parallax effect. In turn, the authors ensured the least possible pressure was applied through the transducer to minimize such tissue compression. This was achieved by using sufficient coupling gel, maintaining the probe perpendicularly to the skin, and continually inspecting the live ultrasound feed.[15] Establishing a standardized measurement methodology can significantly improve the accuracy of SAT thickness determination.[27] Therefore, our scanning protocol followed a consistent pre-determined measuring pattern for localizing the ideal center of each US scan in the study area. Secondly, a disadvantage of the ultrasound is the relatively narrow field of view which requires multiple scans for evaluating larger surface areas such as the abdomen, forming a greater degree of estimation needed. Calculation precision can also be influenced by not adhering to the liposuction operating area defined by the surgeon pre-operatively. The operation and US scans should remain within the confines of the original operative borders on the patient for maximum consistency. Lastly, liposuction volumes obtained from all patients were of relatively small volumes (average 214mL). Future work will emphasize evaluating the technology and the effectiveness of regional fat volume estimation in a clinical study where a wider distribution of volumes and anatomical locations are collected for analysis. In turn, the authors hope to develop protocols for other fat transfer procedures.

Conclusion

This pilot study aimed to develop a quick and inexpensive tool to measure patients' fat volume towards improving procedures that manipulate adipose tissue. Using ultrasound, a readily available, safe, and affordable modality, paired with SAT-Map software, the authors presented the potential this novel technique holds for volume estimation and three-dimensional graphic representation of fat distribution. Subsequently, such a companion tool supports surgical planning and diminishing complications in plastic and reconstructive surgery. Using liposuction as the surrogate procedure, the Bland Altman agreement analysis described a high agreement (within 95% CI) between the ultrasound-based estimations and clinical results, further validating the use-case of SAT-Map. Our work will contribute to the advancement of liposuction by continuously developing the first combined software tool that objectively measures fat volume, with future intentions of developing real-time guidance, intra-operative feedback, and verisimilitude representation of fat profiles. Ultimately, SAT-Map brings an innovative scientific touch to the artistic aspect of aesthetic and reconstructive surgeries.

References

1. Azzi AJ, Hilzenrat R, Viezel-Mathieu A, Hemmerling T, Gilardino M. A review of objective measurement of flap volume in reconstructive surgery. Plast Reconstr Surg Glob Open. 2018;6(5):e1752.

2. Azzi AJ, Lafreniere AS, Viezel-Mathieu A, Hemmerling TM, Gilardino M. Objective quantification of liposuction results. J Cutan Aesthet Surg. 2018;11(3):105-109.

3. Chia CT, Neinstein RM, Theodorou SJ. Evidence-based medicine: Liposuction. Plast Reconstr Surg. 2017;139(1):267e-274e.

4. Schlecht I, Wiggermann P, Behrens G, et al. Reproducibility and validity of ultrasound for the measurement of visceral and subcutaneous adipose tissues. Metabolism. 2014;63(12):1512-1519.

5. Betz TM, Wehrstein M, Preisner F, Bendszus M, Friedmann-Bette B. Reliability and validity of a standardized ultrasound examination protocol to quantify vastus lateralis muscle. Journal of Rehabilitation Medicine. 2021;53(7)

6. Mechelli F, Arendt-Nielsen L, Stokes M, Agyapong-Badu S. Validity of ultrasound imaging versus magnetic resonance imaging for measuring anterior thigh muscle, subcutaneous fat, and fascia thickness. Methods and Protocols. 2019;2(3):58.

7. Chow I, Alghoul MS, Khavanin N, et al. Is there a safe lipoaspirate volume? A risk assessment model of liposuction volume as a function of body mass index. Plast Reconstr Surg. 2015;136(3):474-483.

8. Connelly LM. Pilot studies. Medsurg Nurs. 2008;17(6):411-2.

9. Johanson GA, Brooks GP. Initial scale development: Sample size for pilot studies. Educational and Psychological Measurement. 2010;70(3):394-400.

10. Isaac S, Michael WB. Handbook in research and evaluation: A collection of principles, methods, and strategies useful in the planning, design, and evaluation of studies in education and the behavioral sciences. Edits publishers; 1995.

11. Hill R, Hamilton WP. What sample size is "enough" in internet survey research? 1998:

12. Julious S. Sample size of 12 per group rue of thumb for a pilot study. Pharmaceutical Statistics. 2005;4:287-291.

13. Van Belle G. Statistical rules of thumb. vol 699. John Wiley & Sons; 2011.

14. Swanson E. The expanding role of diagnostic ultrasound in plastic surgery. Plastic and reconstructive surgery Global open. 2018;6(9):e1911-e1911.

15. Azzi AJ, Lafrenière AS, Gilardino M, Hemmerling T. Ultrasonography technique in abdominal subcutaneous adipose tissue measurement: A systematic review. J Ultrasound Med. 2019;38(4):877-888.

16. Altman DG, Bland JM. Measurement in medicine: The analysis of method comparison studies. Journal of the Royal Statistical Society Series D (The Statistician). 1983;32(3):307-317.

17. Giavarina D. Understanding bland altman analysis. Biochem Med (Zagreb). 2015;25(2):141-151.

18. Hu HH, Nayak KS, Goran MI. Assessment of abdominal adipose tissue and organ fat content by magnetic resonance imaging. Obes Rev. 2011;12(5):e504-15.

19. Kvist H, Sjöström L, Tylén U. Adipose tissue volume determinations in women by computed tomography: technical considerations. Int J Obes. 1986;10(1):53-67.

20. Hernandez TL, Kittelson JM, Law CK, et al. Fat redistribution following suction lipectomy: defense of body fat and patterns of restoration. Obesity. 2011;19(7):1388-1395.

21. Benatti F, Solis M, Artioli G, et al. Liposuction induces a compensatory increase of visceral fat which is effectively counteracted by physical activity: a randomized trial. The Journal of Clinical Endocrinology & Metabolism. 2012;97(7):2388-2395.

22. Bilgili Y, Tellioğlu AT, Unal B, Karaeminoğullari G. Quantitative analysis of liposuction with B mode ultrasound. Aesthetic Plast Surg. 2004;28(4):226-7.

23. Greco RJ. Massive liposuction in the moderately obese patients: A preliminary study. Aesthetic Surgery Journal. 1997;17(2):87-90.

24. Khanna A, Filobbos G. Avoiding unfavourable outcomes in liposuction. Indian J Plast Surg. 2013;46(2):393-400.

25. Fodor PB, Cimino WW, Watson JP, Tahernia A. Suction-assisted lipoplasty: Physics, optimization, and clinical verification. Aesthetic Surgery Journal. 2005;25(3):234-246.

26. Chow I, Alghoul MS, Khavanin N, et al. Is there a safe lipoaspirate volume? A risk assessment model of liposuction volume as a function of body mass index. Plastic and reconstructive surgery. 2015;136(3):474-483.

27. Toomey C, McCreesh K, Leahy S, Jakeman P. Technical considerations for accurate measurement of subcutaneous adipose tissue thickness using B-mode ultrasound. Ultrasound. 2011;19(2):91-96.

28. Woman torso in underwear with medical marks for plastic surgery or liposuction. Accessed Septemeber 2nd, 2021. Envato Elements Pty Ltd

Tables:

Table 2. Baseline characteristics of liposuction participants.

Characteristics	Total
Participants, no.	18
Age, yr. (SD)	47.6 (11.3)
Sex, Female (%)	18 (100 %)
Height, cm (SD)	165.2 (7.0)
Weight, kg (SD)	69.6 (8.4)
BMI, kg/m^2 (SD)	25.6 (2.3)
Procedures per Anatomical Location, no. (%)	
Central Abdomen	5 (11%)
Abdominal Crest (Flank)	20 (45%)
Supra Pubic Abdomen	1 (2%)
Inner Thigh	10 (23%)
Outer Thigh	3 (7%)
Upper Back	2 (5%)
Arm	2 (5%)
Neck	1 (2%)
Total	44 (100%)

Note: Characteristics data presented as mean (SD: Standard Deviation) or number (%).

Table 3. Comparison between SAT-Map volume estimates and clinical liposuction results.

	Clinical Case	Procedure	Ultrasound Estimate (mL)	Clinical Result (mL)	Difference in Methods (mL)	Results Difference (%)
1	P 1 (R)	Outer Thigh	74	65	9	87
2	P 2 (R)	Inner Thigh	124	110	14	87
3	P 2 (L)	Inner Thigh	128	110	18	84
4	P 3 (R)	Abdo Crest	79	75	4	95
5	P 3 (L)	Abdo Crest	103	105	-2	98
6	P 4 (R)	Inner Thigh	155	150	5	97
7	P 4 (L)	Inner Thigh	163	150	13	91
8	P 5 (R)	Inner Thigh	145	140	5	96
9	P 5 (L)	Inner Thigh	158	150	8	95
10	P 6-1 (R)	Back	82	75	7	90
11	P 6-1 (L)	Back	55	50	5	90
12	P 6-2 (R)	Abdo Crest	107	100	7	93
13	P 6-2 (L)	Abdo Crest	125	100	25	75
14	P 7 (R)	Arm	528	450	78	83
15	P 7 (L)	Arm	373	350	23	94
16	P 8	Front Neck	35	35	0	100
17	P 9 (R)	Abdo Crest	430	400	30	93
18	P 9 (C)	Abdo Center	478	450	28	94
19	P 9 (L)	Abdo Crest	330	300	30	90
20	P 10 (R)	Abdo Crest	276	270	6	98
21	P 10 (L)	Abdo Crest	338	320	18	94
22	P 11-1 (R)	Abdo Crest	176	180	-4	98
23	P 11-1 (L)	Abdo Crest	241	220	21	90
24	P 11-2 (R)	Outer Thigh	296	300	-4	99
25	P 11-2(L)	Outer Thigh	313	320	-7	98
26	P 12-1	Abdo Center	585	550	35	94
27	P 12-2	Abdo SPR	161	170	-9	95
28	P 13	Abdo Center	35	35	0	100
29	P 14 (R)	Abdo Crest	221	200	21	90
30	P 14 (C)	Abdo Center	525	500	25	95
31	P 14 (L)	Abdo Crest	217	220	-3	99
32	P 15 (R)	Abdo Crest	174	175	-1	99
33	P 15 (L)	Abdo Crest	127	120	7	94
34	P 16 (R)	Abdo Crest	255	260	-5	98
35	P 16 (C)	Abdo Center	241	250	-9	96
36	P 16 (L)	Abdo Crest	264	260	4	98
37	P 17-1 (R)	Inner Thigh	161	165	-4	98
38	P 17-1 (L)	Inner Thigh	145	150	-5	97
39	P 17-2 (R)	Abdo Crest	353	375	-22	94
40	P 17-2 (L)	Abdo Crest	357	375	-18	95
41	P 18-1 (R)	Inner Thigh	128	120	8	93
42	P 18-1 (L)	Inner Thigh	155	150	5	97
43	P 18-2 (R)	Abdo Crest	231	200	31	85
44	P 18-2 (L)	Abdo Crest	156	150	6	96

Note: SPR: Supra Pubic Region; Abdo: Abdomen; P: Patient; R: Right; C: Center; L: Left.

Figures Legend:

Figure 1. Example of SAT-Map fat profile from 8 randomized US scans in 2D and 3D. Shades of beige and red signify varying depths of the underlying SAT distribution. Darker shades from beige to red represent increasing depth, as displayed on the bar chart to the right. All depth values are in centimetres.

Figure 2. Example of centred numbering pattern for ultrasound scanning protocol with SAT-Map (thigh shown). Adapted from Envato Elements[28].

Figure 3. Comparison of mean volumes between clinical liposuction results and SAT-Map ultrasound estimates. Errors bars represent the standard deviation of the difference between means.

Figure 4. Bland Altman plot for determining agreement between ultrasound modality estimates and clinical liposuction results.

Figures:

Figure 8. Example of SAT-Map fat profile from 8 randomized US scans in 2D and 3D. Shades of beige and red signify varying depths of the underlying SAT distribution. Darker shades from beige to red represent increasing depth, as displayed on the bar chart to the right. All depth values are in centimetres.

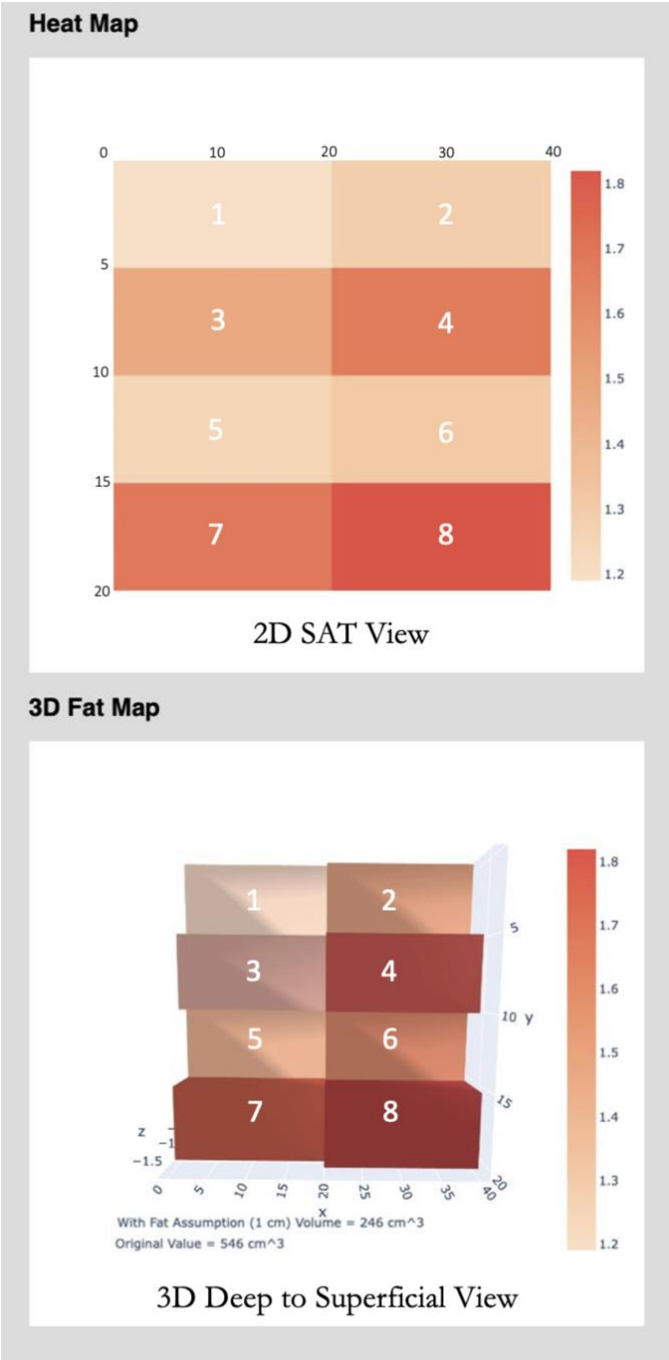


Figure 9. Example of centred numbering pattern for ultrasound scanning protocol with SAT-Map (thigh shown). Adapted from Envato Elements[37].

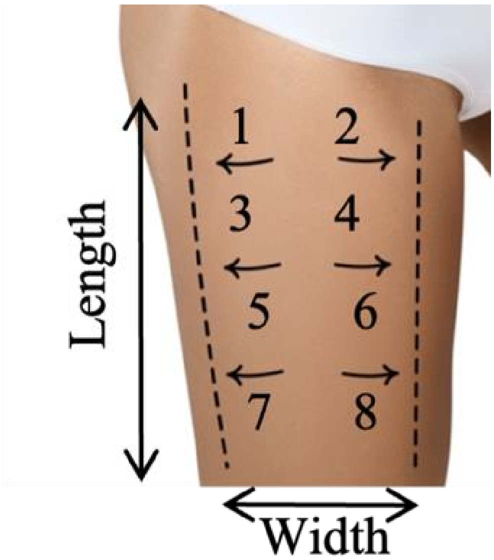


Figure 10. Comparison of mean volumes between clinical liposuction results and SAT-Map ultrasound estimates. Errors bars represent the standard deviation of the difference between means.

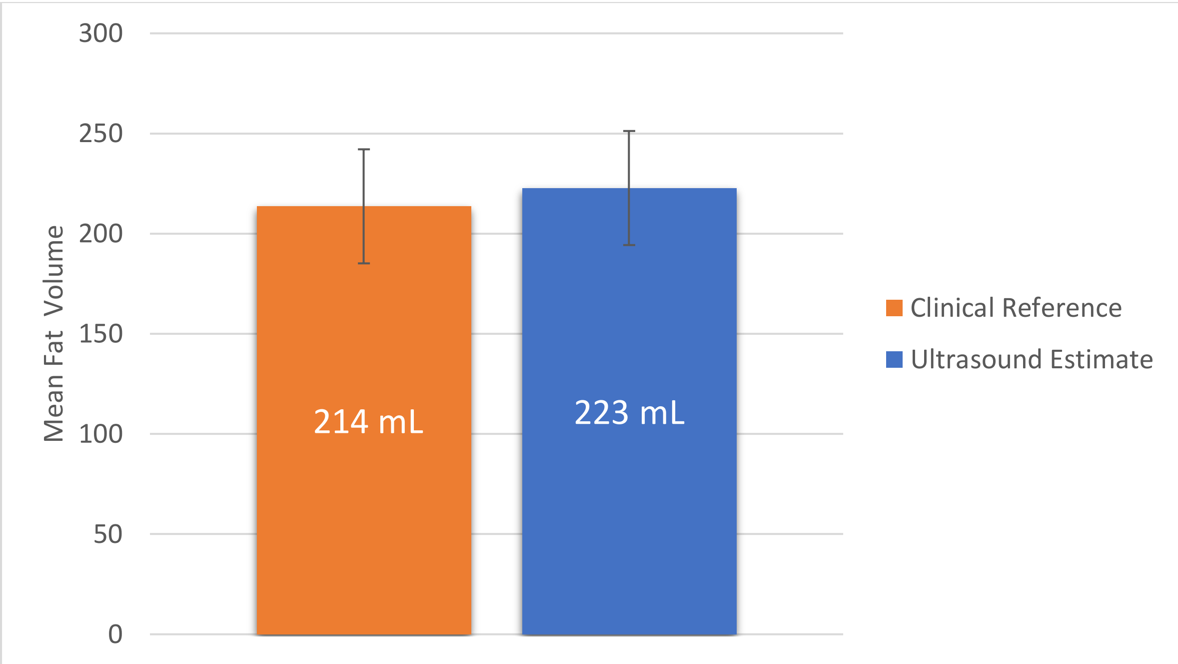
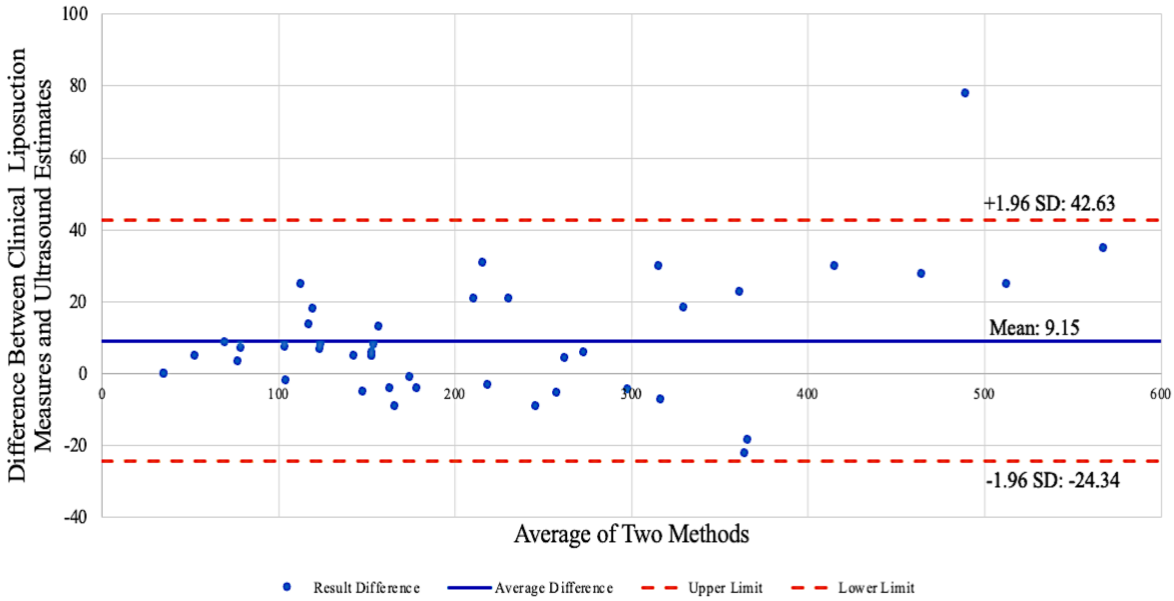


Figure 11. Bland Altman plot for determining agreement between ultrasound modality estimates and clinical liposuction results.



Chapter 4 – Discussion and Future Works

This thesis has addressed different aspects related to adipose tissue simulation and quantification using liposuction as a surrogate procedure for validation. Objective measurement of soft tissues can offer a window toward improving safe pre-operative planning, effective fat transfer and improving patient outcomes in plastic and reconstructive surgery. Chapter 2 sought to provide insight by detailing a new software tool combined with ultrasound imaging. Following the successful development of SAT-Map, chapter 3 investigated the accuracy of the pilot software through the agreement between dry lipoaspirate collected from liposuction procedures and ultrasound estimates with encouraging results. Overall, the above works are the first step toward implementing a novel standard in adipose tissue assessment and encouragingly paving the way toward widespread application in plastic surgery.

Generally speaking, pre-operative topographical markings are a vital reference source for plastic surgeons. Although methods and patterns may differ in liposuction, markings represent the surgical plan for fat removal.[12] Due to gravity, when a patient is lying on the surgical table, fat deposits will shift into disproportionate areas altering their figure. Topographic marking is often performed in the standing position to conceptualize the procedure, provide reference intra-operatively and optimize post-operative results.[13] SAT-Map follows this same approach (scans taken standing) to provide the most accurate representation and volumetric estimations of the regional fat. Yet, the current 2D and 3D representations are displayed using rectangular segments (grid pattern) rather than curvilinear models, which more closely represent human morphology. One study[14] utilized grid markings for liposuction in various areas and concluded that grid patterns are an effective marking technique associated with a low incidence of contour-related complications. Naturally, successful liposuction depends on many factors relating to personal practice. However, grid pattern markings may aid in providing a more systematic approach to fat removal and minimizing accidental duplication or omission of treated areas. In addition, simulating rectangular segments is a less complicated computational task than constructing geometrically lifelike outlines. Although satisfactory in its current state, the future of SAT-Map lies in evolving the software with verisimilitude models that can be overlaid on patient images to benefit surgical planning further.

The current ultrasound measurement methodology includes a technical limitation mentioned in Chapter 3. Eight ultrasound images are needed for any region to ensure consistency when estimating fat volumes and displaying the fat distribution. A narrow field of view from the portable ultrasound probe indicates that multiple scans are required to evaluate a given anatomical region, such as the abdomen. Fewer measurements may provide insufficient data to create clinically accurate fat distribution and volume estimations. Future works should correlate the optimal number of ultrasound scans to common anatomical areas undergoing liposuction rather than a standard set for all locations. Thus, distinguishing the minimum necessary measurements to ensure satisfactory performance of SAT-Map can optimize time allocation and reliability.

Anatomical regions investigated for SAT-Map and plastic surgery are not uniform per the natural morphology of the human body. For example, the abdominal muscles medially differ from those laterally, causing a difference in shape, depth, and contour. Yet, under the narrow linear ultrasound view, subcutaneous fat is presented as a generally uniform region even though the underlying tissues may not. In the context of an ultrasonographer, the non-uniformity between different muscle regions across the abdomen should not limit the ability to collect ultrasound measurements within the confines of the surgical boundaries established. However, this distinction between the adjacent regions is vital as the ultimate goal is to obtain optimal contour and surgical outcomes, leading to improved patient satisfaction. To that end, the ambition of plastic surgery is to marry the anatomy of adjacent regions. This often signifies that the nearly complete removal of adipose tissue is not always the appropriate approach. The trial study in Chapter 3 focused mainly on correlating fat estimations with adipose tissue removal in the study areas. This trial run was performed to ensure the clinical accuracy of the software. Yet, the data obtained is a calibration for the technology's multiple roles in supporting future patients and surgeons. Primarily, SAT-Map can deliver a comprehensive visual guide for surgical planning where aesthetic surgical decision-making is complemented by a software tool providing critical information such as morphological distribution, localized volumetric data, and estimated safe total removable fat. Therefore, the goal of the technology is not to continually perform the complete removal of fat but to optimize pre-operative planning to achieve patient-specific surgical objectives.

Previous chapters have thoroughly investigated the prospective advantages of an objective assessment modality for adipose tissue in the pre-operative setting. However, to construct a wide-ranging companion tool, further research is necessary into future applications of SAT-Map in other stages of surgery. Specifically, intraoperative ultrasound imaging can be adapted with SAT-Map to provide a real-time outline and localization of fat deposits. In plastic surgery, multiple studies have revealed how ultrasound guidance has assisted surgeons with various procedures, such as surgeon-administered nerve blocks[15], circumventing implants during breast fat grafting[16], guidance for nerve resection[17] and cephalic vein transposition[18], among others.[19] As such, in addition to pre-operative planning, our software can be adapted similarly for surgical navigation and guidance for procedures involving fat manipulation, primarily free flaps for reconstructive purposes. Real-time simulation and quantification of free flaps and donor sites can provide significant advantages to current subjective approaches. A recent systematic review[20] specified the great value in the ability to accurately determine flap volumes where harvesting minimal flap volume can significantly reduce donor site morbidity and concurrently improve patient quality of life. Analogous to the works on liposuction presented in the above chapters, objective measurements of flaps can lead to improved symmetry, patient satisfaction and, ultimately, surgical outcomes.

Chapter 5 – Conclusions

This project presents a new software paired with ultrasound imaging that objectively simulates and calculates clinically accurate adipose tissue distribution and volume. SAT-Map is a user-friendly web-based tool offering multiple advantages over current methods of SAT assessment. MRI and CT are excellent modalities for soft tissue characterization. However, they are cost-intensive and not readily accessible. Alternatively, ultrasonography proved to be an excellent adjunct to SAT-Map on account of its availability, affordability, and similar capacity for quantitatively assessing SAT promptly. The development of SAT-Map software presents promising prospects in the implementation of 2D and 3D virtual simulations paired with objective quantification of adipose tissue in plastic and reconstructive surgery. This was echoed by the pilot trial, which revealed excellent agreement between ultrasound estimates and liposuction aspirate volumes. Our work will continue pushing new boundaries by continuously evolving the concept of objective pre-operative planning in fat-transfer-based operations. Future work will focus on further developing the current status of the software with verisimilitude models, additional validation of SAT-Map's accuracy with extensive clinical trials and developing new protocols for other fat transfer procedures. Ultimately, the development of an optimized and objective assessment tool, is to provide surgeons and patients with greater confidence in the planning and execution of invasive surgical procedures.

Chapter 6 – References

1. Kayastha D, Vakharia KT. The evolving roles of computer-based technology and smartphone applications in facial plastic surgery. Current Opinion in Otolaryngology & Head and Neck Surgery. 2019;27(4):267-273.

2. García-Mato D, Ochandiano S, García-Sevilla M, et al. Craniosynostosis surgery: workflow based on virtual surgical planning, intraoperative navigation and 3D printed patient-specific guides and templates. Scientific reports. 2019;9(1):1-10.

3. Chia CT, Neinstein RM, Theodorou SJ. Evidence-based medicine: Liposuction. Plast Reconstr Surg. 2017;139(1):267e-274e.

4. Macadam SA, Bovill ES, Buchel EW, Lennox PA. Evidence-based medicine: autologous breast reconstruction. Plastic and reconstructive surgery. 2017;139(1):204e-229e.

5. Khouri RK. Current clinical applications of fat grafting. Plastic and reconstructive surgery. 2017;140(3):466e-486e.

6. Hernandez TL, Kittelson JM, Law CK, et al. Fat redistribution following suction lipectomy: defense of body fat and patterns of restoration. Obesity. 2011;19(7):1388-1395.

7. Benatti F, Solis M, Artioli G, et al. Liposuction induces a compensatory increase of visceral fat which is effectively counteracted by physical activity: a randomized trial. The Journal of Clinical Endocrinology & Metabolism. 2012;97(7):2388-2395.

8. Azzi AJ, Lafreniere AS, Viezel-Mathieu A, Hemmerling TM, Gilardino M. Objective quantification of liposuction results. J Cutan Aesthet Surg. 2018;11(3):105-109.

9. Schlecht I, Wiggermann P, Behrens G, et al. Reproducibility and validity of ultrasound for the measurement of visceral and subcutaneous adipose tissues. Metabolism. 2014;63(12):1512-1519.

10. Betz TM, Wehrstein M, Preisner F, Bendszus M, Friedmann-Bette B. Reliability and validity of a standardized ultrasound examination protocol to quantify vastus lateralis muscle. Journal of Rehabilitation Medicine. 2021;53(7)

11. Mechelli F, Arendt-Nielsen L, Stokes M, Agyapong-Badu S. Validity of ultrasound imaging versus magnetic resonance imaging for measuring anterior thigh muscle, subcutaneous fat, and fascia thickness. Methods and Protocols. 2019;2(3):58.

12. Zocchi MMDPD. Clinical aspects of ultrasonic liposculpture. Perspectives in Plastic Surgery. 1993;7(02):153-172.

13. Jackson RF. Superficial liposculpture: Rationale and technique. *Liposuction*. Springer; 2006:185-197.

14. Chang KN. The use of intraoperative grid pattern markings in lipoplasty. Plastic and Reconstructive Surgery. 2004;114(5):1292-1297.

15. Wheble GA, Tan EK, Turner M, Durrant CA, Heppell S. Surgeon-administered, intra-operative transversus abdominis plane block in autologous breast reconstruction: a UK hospital experience. Journal of Plastic, Reconstructive & Aesthetic Surgery. 2013;66(12):1665-1670.

16. Oni G, Chow W, Ramakrishnan V, Griffiths M. Plastic surgeon–led ultrasound. Plastic and Reconstructive Surgery. 2018;141(2):300e-309e.

17. Adler AC, Smith DI, Parikh PM. Chronic pain localized to the iliohypogastric nerve: treatment using an ultrasound-guided technique of hydrodissection for catheter placement as a guide for surgical iliohypogastric nerve resection. Plastic and Reconstructive Surgery. 2014;134(1):182e-183e.

18. Senchenkov A. Small-incision cephalic vein transposition technique with surgeon-performed intraoperative ultrasound mapping. Plastic and Reconstructive Surgery. 2015;135(3):651e-652e.

19. Miller JP, Carney MJ, Lim S, Lindsey JT. Ultrasound and plastic surgery: clinical applications of the newest technology. Annals of Plastic Surgery. 2018;80(6S):S356-S361.

20. Azzi AJ, Hilzenrat R, Viezel-Mathieu A, Hemmerling T, Gilardino M. A review of objective measurement of flap volume in reconstructive surgery. Plast Reconstr Surg Glob Open. 2018;6(5):e1752.