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Cross-sectional area of the abdomen predicts complication incidence in patients undergoing sternal reconstruction

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Abstract

Background—Sternal reconstruction with vascularized flaps is central to the management of sternal wound infections and mediastinitis but carries a high risk of complications. There is a need to identify reliable predictors of complication risk to help inform patients and clinicians in preparation for surgery. Unfortunately, body mass index and serum albumin may not be reliable predictors of complication rates. Analytic morphomics provides a robust quantitative method to measure patients' obesity as it pertains to their risk of complications in undergoing sternal reconstruction.

Methods—We identified 34 patients with preoperative computed tomography scans of the abdomen from a cohort of sternal reconstructions performed between 1997 and 2010. Using semiautomated analytic morphomics, we identified the patients' skin and fascia layers between the ninth and 12th thoracic spine levels; from these landmarks, we calculated morphomic measurements of the patients' abdomens, including their total body cross sectional area and the cross sectional area of their subcutaneous fat. We obtained the incidence of complications from chart review and correlated the incidence of complications (including seroma, hematoma, recurrent wounds, mediastinitis, tracheostomy, and death) with patients' morphomic measurements.

Results—Sixty-two percent of patients ($n = 21$) suffered complications after their operation. Those who suffered from complications, relative to those who did not have complications, had increased visceral fat area (12,547.2 mm² versus 6569.9 mm², $P = 0.0080$), subcutaneous fat area (16,520.2 mm² versus 8020.1 mm², $P = 0.0036$), total body area (91,028.6 mm² versus 67,506.5 mm², $P = 0.0022$), fascia area (69,238.4 mm² versus 56,730.9 mm², $P = 0.0118$), total body circumference (1101.8 mm versus 950.2 mm, $P = 0.0017$), and fascia circumference (967.5 mm

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Disclosure

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versus 868.1 mm, $P = 0.0077$). We also demonstrated a significant positive correlation between the previously mentioned morphomic measurements and the incidence of complications in multivariate logistic regression models, with odds ratios ranging from 1.19–3.10 (P values ranging from 0.010–0.022).

Conclusions—Increases in abdominal morphomic measurements correlate strongly with the incidence of complications in patients undergoing sternal reconstruction. This finding may influence preoperative risk stratification and surgical decision making in this patient population.

Keywords

Sternal reconstruction; Morphomics; Subcutaneous fat

1. Introduction

The median sternotomy is an essential surgical approach for many cardiac and thoracic operations. Many of the patients who require cardiothoracic surgery through a median sternotomy are those patients who are already at an increased risk of developing surgical complications. Complications after median sternotomy have severe repercussions for patient outcomes. Sternal wound infections are one such serious complication and can lead to dehiscence of the sternal wound [1]. Dehiscence is a serious complication occurring in 0.2%–5% of all median sternotomy cases [2–5]. Obese patients are, in particular, at increased risk for infection and dehiscence after median sternotomy, although not all obese patients will experience these complications [5–9]. For this reason, it is crucial to find more precise ways to stratify these patients by their surgical risk.

Aggressive debridement of nonviable tissues followed by reconstruction using vascularized flaps is a common technique for the management of sternal wound infection resulting in dehiscence. This surgical approach has resulted in a decrease in infections and mortality in this patient population [10]. However, the operation remains one relatively fraught with complications. One study found that the rate of reoperation for complications—including infection, dehiscence, and tissue necrosis—in flap repairs for sternal reconstruction is nearly 20%. They found that diabetes mellitus, hypertension, and congestive heart failure are significant predictors of the aforementioned complications of sternal reconstruction [11].

There is a paucity of research; however, linking increased abdominal fat specifically to clinical outcomes in sternal reconstruction, rather than obesity measured by body mass index (BMI). In this study, we apply morphomic analysis, the measurement of patient anatomy from routine preoperative computed tomography (CT) scans, to identify patient morphologic characteristics that correlate with a higher risk of surgical complications in this patient population.

2. Methods

2.1. Study population

After receiving Institutional Review Board approval, a comprehensive retrospective electronic medical record review was conducted on all patients who underwent sternal

reconstruction at the University of Michigan Health System between 1997 and 2010. Only patients who had an abdominal CT scan related to their preoperative evaluation were included in this study; these scans were not performed for the sole purpose of this study. We identified a total of 34 patients who underwent sternal reconstruction with vascularized flaps and received preoperative abdominal CT scans. Patient demographics, preoperative risk factors, surgical indications, operative technique and details, and postoperative complications including recurrence rates were obtained from the clinical records. Follow-up data were extracted from analysis of office charts, hospital and outpatient electronic medical records, and postoperative abdominal CT scans.

2.2. Recurrence and complication assessment

Complications in this cohort of patients included, but were not limited to, seroma, hematoma, infections, recurrent wounds, mediastinitis, tracheostomy, and death. Sternal wound recurrences after reconstruction were recorded only if unequivocally documented through imaging studies or physical examination by a plastic surgeon, general surgeon, or emergency room physician. Infection was recorded only if documented by a plastic or general surgeon and required the presence of surrounding cellulitis or a purulent discharge from the wound. A chronic wound was defined as any postoperative wound requiring packing.

2.3. Analytic morphomics

Preoperative abdominal CT scans were processed using semiautomated algorithms programmed in MATLAB version 13.0 (The MathWorks, Inc, Natick, MA) as previously described [12–14]. These algorithms use novel, semi-automated, high-throughput techniques that we have named analytic morphomics.

The initial processing step identified individual vertebral levels on each patient's scan from T9 through T12, which served as anatomic landmarks for standardization for the subsequent analyses. The next processing step identified the *linea alba* and the anterior abdominal skin along the midline at each vertebral level from which the skin layer and fascia layer are extrapolated (Fig. 1A). We then isolated the subcutaneous (Fig. 1B) and visceral (Fig. 1C) fat portions within the total body area and fascial area by density in Hounsfield units to calculate the cross-sectional surface area of these regions.

2.4. Statistical analysis

We performed two-sample comparisons between patients with and without complications for age, BMI, gender, diabetes mellitus status, smoking status, and serum albumin using Student *t*-test. Used *t*-tests to compare the morphomic measures identified to describe patient obesity—the visceral fat area, subcutaneous fat area, total body area, fascia area, total body circumference, fascia circumference, body depth, and body width—between those who had complications and those who did not. Through multiple logistic regression analysis, we see the adjusted effects of these morphomic factors after we control for the basic demographic covariates of age, BMI, gender, diabetes mellitus status, smoking status, and serum albumin. For these analyses, receiver operating characteristic (ROC) curves were then developed plotting 1-specificity (*y*-axis) *versus* the sensitivity (*x*-axis) for each of the morphomic

variables and the area under the curve was determined. Pearson correlation coefficient between the morphomic indices measured at each individual vertebral level and the average of these values across all studied vertebral levels was determined. Two-sample *t*-tests and Pearson correlations were performed with Microsoft Excel (Seattle, WA), and logistic regression analysis was performed using SPSS (International Business Machines Corporation of Armonk, NY).

Finally, to perform a *post-hoc* power analysis of our models given sample size, we began by estimating linear regressions and the associated R^2 values using each of our six morphomic values as dependent variables and the demographic covariates as independent variables. We then used the program nQuery Advisor (Statistical Solutions, Cork, Ireland) and treated the comparison of morphomic values between patients with complications and those without complications as a *t*-test with equal variance to calculate the number of patients needed to detect the differences observed in morphomic values, or N . Then, we multiplied the N values by a variance inflation factor using the R^2 from the original linear regressions to obtain an approximation of the number of patients (N_p) theoretically required to detect an effect with $\alpha = 0.05$ and a power of 80%. We also used the same model to estimate the power we actually achieved from our analyses given the incidence of complications in our study population, given $\alpha = 0.05$.

3. Results

3.1. Patient demographics

Sixty-two percent of the patients in the series had a complication ($n = 21$). The mean ages in the cohort of patients who did and did not experience complications were 59.1 y (standard deviation = 9.5) and 61.7 y (standard deviation = 9.1), respectively ($P = 0.44$). The proportion of females in the group without complications was 0.54 compared with 0.24 in the group that suffered from complications ($P = 0.10$). Forty-six percent of those who did not have complications had a history of tobacco use compared with 35% of those who suffered from complications ($P = 0.54$). The difference in the percentage of patients with diabetes mellitus in the complication, and no complication groups was statistically significant (48% [$n = 10$] versus 15% [$n = 2$], respectively, $P = 0.043$). Serum albumin averaged 3.5 in the patients who did not have complications, and 3.2 in those who did ($P = 0.26$). The average BMI of patients with and without complications was 32.5 and 27.5, respectively ($P = 0.04$).

3.2. Morphomic values correlate with surgical outcomes

Patients with complications had increased visceral fat area relative to those who did not (12,547.2 mm² versus 6569.9 mm², $P = 0.0080$, Fig. 2). Patients with complications also had increased subcutaneous fat area (16,520.2 mm² versus 8020.1 mm², $P = 0.0036$, Fig. 3). Those who experienced complications also had higher total body area (91,028.6 mm² versus 67,506.5 mm², $P = 0.0022$, Fig. 4). We also found increase in the fascia area in the group with complications (69,238.4 mm² versus 56,730.9 mm², $P = 0.0017$, Fig. 5). The total body circumference was also increased in the group that suffered from complications (1101.8 mm versus 950.2 mm, $P = 0.0017$, Fig. 6). Finally, patients with complications had a higher

fascia circumference than those who did not (967.5 mm *versus* 868.1 mm, $P = 0.0077$, Fig. 7). Table 1 summarizes these findings.

Furthermore, we find that these morphologic factors achieved predictive power with areas under the ROC ranging from 0.76–0.83.

3.3. These relationships are maintained in multivariate models

When we applied multivariate regression analyses to control for the factors of age, BMI, gender, diabetes mellitus status, smoking status, and serum albumin, the associations we found through t -testing and correlation were maintained (Table 2). The only other near significant covariate we found was in the model for subcutaneous fat area *versus* complications. In this model, female gender was somewhat protective (odds ratio = 0.16) of complications, but this result did not reach statistical significance ($P = 0.06$).

3.4. Morphomics measured at a single vertebral level correlate with their average value across multiple vertebral levels

At each of the individual vertebral levels for which we calculated morphomic indices, we found a significant degree of correlation between these values and the previously discussed averages of the values calculated at all of the studied vertebral levels (Table 3).

3.5. Post-hoc power analysis

In our models, to estimate the effect of our demographic covariates on the six morphomic values discussed previously, we found a wide array of R^2 values, which ranged from 0.17–0.68. Accordingly, the number of patients theoretically required to detect an effect (N_p) varied considerably between models ranging from 41.6–87.6 patients. Our estimate of the actual power achieved for each model created ranged from 66%–82% (Table 4).

4. Discussion

In this study, we demonstrate that the development of complications after sternal reconstruction is associated with increases in morphomic measurements of the abdomen and abdominal fascia and the visceral and subcutaneous fat of the abdomen. These associations are upheld even after controlling for demographic covariates. Furthermore, these morphomic measurements achieved much greater statistical significance than BMI or serum albumin. When testing these models by calculating their ROC, we find that they demonstrate good predictive ability with high area under the receiver operating characteristic curve values. These findings show that our morphomic measurements of patient obesity are more predictive of complications in patients undergoing sternal reconstruction than traditional measures of health and nutritional status. With this knowledge, we have built models to better identify patients at increased risk for complications after sternal reconstruction, which will improve preoperative risk stratification and give clinicians the ability to optimize the care of these high-risk patients.

There are currently many options for the management of chest wall dehiscence ranging from prosthetic measures to local tissue flaps. The goal of this operation is to restore function and structure to the wound site; the type of reconstruction used must take into account the extent

and location of the defect, the presence of infection, the previous existence of a tumor, prior radiation therapies, and the patient's individual needs [15,16]. A 2009 study showed that one-step debridement and muscle flap reconstruction results in significant decreases in morbidity, mortality, and length of hospital stay in patients with deep sternal wound infection [17]. A 2002 study also showed that one-stage debridement and reconstruction is better than conventional repair techniques [18]. Among the most commonly used donor sites for chest wall reconstruction are the pectoralis major and rectus abdominis as either muscle or myocutaneous flaps [19]. Immediate debridement combined with pectoralis major flap has been shown to minimize morbidity and mortality [20]. The choice between donor sites should be influenced by the location of the wound; pectoralis flaps provide superior wound coverage in the superior infection, whereas rectus flaps are superior in covering inferior infections and wounds [21]. For larger defects, combining pectoralis and omentum flaps can achieve rates of complication comparable with single muscle flaps for smaller defects [22]. Muscle flaps are currently one of the preferred methods for repairing sternal defects, and the development of these techniques has dramatically reduced the mortality in these patients from 40%–5% and decreased the time that patients must spend in the hospital to an average of 12 d [23]. Although muscle flap coverage of the wound has been a tremendous advance in the management of chest wall dehiscence, they also may be insufficient for very large or morbid defects. Pedicled flaps and microsurgical procedures may be used to improve blood flow and provide donor tissues from more distal sites on the body [24]. Another reconstructive option, omentum flaps, may prove to have decreased mortality and complication rates than muscle flaps [25]. Omental flaps are unlikely to affect our ability to calculate risk in these patient populations using the methods described in this article, as the morphomic measurements are obtained from preoperative CT scans. With the ability to identify patients at increased risk for complications, clinicians may indicate for these patients the procedures that minimize the risk of complications.

Regardless of the type of reconstructive operation chosen, there remains a high risk of complications associated with surgical repair of sternal infections. It is, therefore, essential for the surgeon to consider their patients' risk factors in planning their clinical course. Obesity has long been established as a risk factor for postoperative complications, as it inhibits wound healing by decreasing vasculogenesis [26]. It is associated with an increased risk of postoperative complications in cardiac operations [8]. However, there is still a paucity of evidence establishing the mechanism or exact cause of the increased risk; this is, in part, due to the inconsistent definition of obesity across studies [27]. Accordingly, we identify in this study more precise measurements of obesity, which we hope will provide a more consistent definition of obesity as it pertains to patients' increased risk of complications using already obtained CT scans. Our demonstration that the morphomic measurements taken at one vertebral level correlate with the average measurements used in this study suggests that measurements of subcutaneous fat from a single CT slice may provide a more rapid but equally robust proxy for measuring abdominal obesity. This may facilitate the clinical use of these findings before the development of clinical software tools that automate our processes.

Beyond the known risks of obesity, several studies have demonstrated the association between visceral fat accumulation and surgical complications. One previous study has

shown that obese patients, defined by having increased visceral fat volumes, require longer operative times, have more blood loss, and have a higher incidence of surgical site infection than nonobese patients undergoing colorectal resection [28]. Another study has demonstrated that visceral fat area is a more useful measurement than BMI for predicting clinical outcomes in colectomy patients [29]. Interestingly, in this study, we found that subcutaneous fat is more predictive of complications than visceral fat. This distinction may be an artifact of the vertebral levels that we chose to analyze in this study, T9–T12. We identified these levels to improve capture because they are often included in thorax CT scans. However, these levels may be above the levels of the most visceral fat accumulation, which may limit our study in its ability to capture the importance of visceral fat. These vertebral levels are also closer to the surgical site in these patients, meaning that subcutaneous fat in the region may increase the risk of local complications such as surgical site infection. However, our *post-hoc* power estimates demonstrate that although this study population is small, the effects that we observed likely represent a real difference between those patients who had complications and those who did not. If it is truly the case that subcutaneous fat is a more important marker of surgical risk, it may circumvent the need to perform a CT scan for preoperative risk stratification. Simple measurements with a skin caliper may provide sufficient information to assess the risk afforded by extraneous subcutaneous fat. Further studies will be necessary to determine the significance of subcutaneous *versus* visceral fat in preoperative risk stratification and to determine if such a strategy is feasible for risk stratification. As yet, given our relatively small study population, it may be premature to assign quantitative thresholds for morphomic values below which risk is minimized. Furthermore, it remains to be seen what interventions could be performed on high-risk patients to improve their risk profile. Accordingly, we do not yet recommend universal preoperative CT scanning in this patient population, as the costs and risks of such imaging must be weighed against any decrease in morbidity that may be achievable based on our knowledge of these patients' morphomics.

In this cohort of patients, we initially were interested in characterizing the morphomics of the chest and defining what, if any, correlations exist between these values and the incidence of complications. However, we found that the morphomics of the chest were difficult to define and less predictive than those of the abdomen. A higher proportion of the abdomen's cross-sectional area is composed of fat relative to the chest (which contains the lungs), and the fat in the abdomen appears to be more variable between individuals than that of the chest. In this respect, the results of this study are somewhat intuitively predictable; many obese individuals have an accumulation of excess abdominal fat, so assuming that obesity is associated with surgical complications, this is an expected result. However, our findings may further elucidate the reason that obesity is associated with the development of complications. Specifically, these findings seem to implicate truncal obesity over other forms of obesity as responsible for the development of complications. Patients with truncal obesity, as opposed to other body types at a similar BMI, will have relatively increased morphomic measurements of the abdomen (such as total body area) compared with BMI. They suggest that patients with primarily truncal obesity are at relatively greater risk for complications than would be expected based on their BMI alone. Furthermore, the integrity of the sternum is inherently compromised in this patient population. It is, therefore, difficult

to measure the morphomic features of this bone or to use it as an anatomic landmark in defining the dimensions of adjacent structures. We are considering improved methods to define the morphomics of the pectoralis muscles, which we hope to use in future studies to investigate the significance of this muscle's size and quality with regards to surgical outcomes.

5. Conclusions

We conclude that morphomic measurements indicating increases in abdominal obesity in the levels of T9 through T12 are associated with an increase in complications after sternal reconstruction. We hope that these findings will influence preoperative risk stratification and surgical decision making in this patient population to minimize surgical risk in these vulnerable patients. In future studies, we hope to create predictive models with clinical utility to better elucidate the effects of these morphomic values.

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Fig. 1.

Preoperative CT slice of patient's abdomen taken at T11. (A) Skin labeled with purple contour and fascia labeled with yellow contour. (B) Subcutaneous fat is filled in red. (C) Visceral fat is filled in red.

Fig. 2. Box-and-whisker plot of visceral fat area (square millimeter) in patients who suffered from complications compared with those who did not. $P < 0.05$.

Fig. 3. Box-and-whisker plot of subcutaneous fat area (square millimeter) in patients who suffered from complications compared with those who did not. $P < 0.05$.

Fig. 4. Box-and-whisker plot of total body area (square millimeter) in patients who suffered from complications compared with those who did not. $P < 0.05$.

Fig. 5. Box-and-whisker plot of fascia area (square millimeter) in patients who suffered from complications compared with those who did not. $P < 0.05$.

Fig. 6. Box-and-whisker plot of total body circumference (millimeter) in patients who suffered from complications compared with those who did not. $P < 0.05$.

Fig. 7. Box-and-whisker plot of fascia circumference (millimeter) in patients who suffered from complications compared with those who did not. $P < 0.05$.

Table 1

Morphomic measurements in patients who did and did not suffer complications, with *P* values showing statistical significance.

Patient group	Visceral fat area (mm ²)	Subcutaneous fat area (mm ²)	Total body area (mm ²)	Fascia area (mm ²)	Total body circumference (mm)	Fascia circumference (mm)
Complication	12,547.2	16,520.2	91,028.6	69,238.4	1101.8	967.5
No complication	6569.9	8020.1	67,506.5	56,730.9	950.2	868.1
<i>P</i> value	0.0080	0.0036	0.0022	0.0118	0.0017	0.0077

Table 2

Summary of multivariate logistic regression models for each morphomic measurements, including odds ratio of complications (with 95% confidence interval), AUROC, and other covariates approaching significance.

Morphomic	<i>P</i> value and OR	AUROC	Other covariates
Visceral fat area (per 10 cm ²)	OR = 1.20 (1.03–1.40) <i>P</i> = 0.022	0.78	None
SubQ fat area (per 10 cm ²)	OR = 1.19 (1.03–1.36) <i>P</i> = 0.017	0.83	Gender (female) <i>P</i> = 0.06, OR = 0.16 (0.02–1.08)
Total body area (per 100 cm ²)	OR = 1.92 (1.16–3.19) <i>P</i> = 0.012	0.82	None
Fascia area (per 100 cm ²)	OR = 2.13 (1.11–4.07) <i>P</i> = 0.022	0.76	None
Total body circumference (per 10 cm)	OR = 3.00 (1.30–6.95) <i>P</i> = 0.010	0.82	None
Fascia circumference (per 10 cm)	OR = 3.10 (1.24–7.75) <i>P</i> = 0.016	0.77	None

AUROC = area under the receiver operating characteristic curve; OR = odds ratio; SubQ = subcutaneous.

Table 3

Pearson correlation coefficients between morphomic values measured at each individual vertebral level and the average of morphomic values across all levels studied. All correlations are statistically significant with $P < 0.001$.

Vertebral level	Visceral fat area (mm ²)	Subcutaneous fat area (mm ²)	Total body area (mm ²)	Fascia area (mm ²)	Total body circumference (mm)	Fascia circumference (mm)
T9	0.952*	0.977*	0.994*	0.990*	0.993*	0.992*
T10	0.975*	0.980*	0.997*	0.998*	0.991*	0.999*
T11	0.985*	0.985*	0.998*	0.996*	0.989*	0.996*
T12	0.983*	0.969*	0.993*	0.989*	0.996*	0.992*

* $P < 0.001$.

R^2 values, estimated number of patients needed to observe an effect, and estimated achieved power for each morphomic value.

Table 4

Statistic	Visceral fat area (mm ²)	Subcutaneous fat area (mm ²)	Total body area (mm ²)	Fascia area (mm ²)	Total body circumference (mm)	Fascia circumference (mm)
R^2	0.26	0.17	0.46	0.68	0.45	0.68
N_p	50.4	44.3	45.4	87.6	41.6	76.6
Achieved power (%)	66	70	79	66	82	72