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Is There an Indication for Digital Subtraction Angiography in the Assessment of Irradiation-Induced Vascular Damage before Free Flap Surgery by the Means of the Internal Mammary Vessels?

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Abstract

Secondary breast reconstruction is increasingly performed after postmastectomy radiotherapy. Damage to blood vessel walls is one of the adverse effects of irradiation therapy, which may jeopardize reconstructive free flap surgery. It would be of great importance to be informed about the quality of the recipient vessel before reconstructive surgery. The aim of this study was to prospectively assess the value of preoperative angiography in the assessment of radiation-induced arterial damage and to relate the findings to the degree of vascular damage found during the operation and with histology. This study included women who had been treated with thoracic radiotherapy and required free flap breast reconstruction. Preoperative angiographic, intraoperative quality and histological findings of vessels were scored and compared together with the occurrence of postoperative complications. In 34 patients a total of 40 free flaps breast reconstruction were performed. Total 21 internal mammary arteries had been within the field of irradiation. In only two out of six patients with aberrant angiographies the internal mammary artery has been within the field of irradiation. This study concludes that damage to the internal mammary vessels cannot always be detected preoperatively by angiography, or even by intraoperative examination.

Keywords
- free flap
- digital subtraction angiography
- histology
- internal mammary artery

Free flap reconstructive surgery is often performed after oncologic resections and adjuvant irradiation therapy.[1] In 1899 it was reported that irradiation can lead to arteritis and atherosclerotic disease,[2–6] and the overall incidence of radiation-related vascular damage in general ranges from 30 to 89%.[7,8]

To date, the accuracy of detection of irradiation damage of arteries with angiography before free flap reconstructions has not been assessed. Hence, the aim of this study was to prospectively assess the value of preoperative angiography in the assessment of radiation-induced arterial damage and to relate the findings to the degree of vascular damage found during the operation and with histology. For this purpose the authors choose to study the internal mammary artery (IMA) in patients scheduled for free flap mammary reconstruction after radiotherapy to the thoracic region.

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Materials and Methods

This study was approved by the Institutional Review Board of the Netherlands Cancer Institute–Antoni van Leeuwenhoek Hospital. Patients gave their written informed consent for the study.

From October 2003 to March 2007, highly selective digital subtraction angiography of the IMAs was preoperatively performed in 34 female candidates for free deep inferior epigastric perforator flap mammary reconstruction. Clinical and treatment data were extracted from the patients' medical and radiotherapy chart and radiation dose plan was used to determine the actual radiation dose delivered to the internal mammary vessels.

A radiologist blinded for the history of the patients scored the angiographies for the anatomy and course of the IMA and its degree of intraluminal atherosclerotic changes.

During free flap breast reconstruction the IMAs and internal mammary veins (IMVs) were dissected by removing the overlying medial part of the rib. Before performing the anastomosis in the subcostal space the vessels were scored for quality of their wall and lumen diameter. Representative 5-mm specimens of both the IMA and the deep inferior epigastric arteries of 25 patients were obtained. All specimens were fixed in 1% paraformaldehyde for 48 hours after which 4 µm thick paraffin embedded cross-sections were made. The sections were stained with hematoxylin and eosin and with Lawson elastin stain.[9] As irradiation may cause a thickening of the media or intima with simultaneous decrease of the luminal diameter in medium-sized arteries,[10,11] the wall-to-lumen area ratio and the media-to-lumen area ratio were calculated.[9] In this measurement the vessel wall was defined as intima and media. All measurements and calculations were done by one investigator (S.H.).

Statistical Analysis

Combining the radiological, intraoperative, and histological observations, the authors calculated the correlation between the results of the various observations, using the chi-square test to assess the predictive value of the angiography for radiation-related vascular damage and surgical outcome. Statistical significance was accepted at p value ≤ 0.05. Distinction was made between internal mammary vessels that had received the full therapeutic radiation dose at the position of the internal mammary vessels, and those that had not.

Patient Characteristics

The 34 women had a mean age of 45 years (range, 32–60 y) and all had previously undergone mediastinal radiotherapy for Hodgkin lymphoma ($n = 2$) or unilateral thoracic radiotherapy because of breast cancer ($n = 32$), a mean of 3.77 years (range, 0.5–17 y) before angiography. The mean total dose had been 43.69 Gy (range, 17.5–50.0 Gy). In 19 of the 32 unilaterally irradiated patients, the internal mammary vessels had been included within the field of radiation. A total of 30 of the 34 patients (36 out of 40 flaps) were treated with chemotherapy before breast reconstruction.

A bilateral internal mammary angiography was performed in 31 women. Unilateral angiography of only the irradiated IMA was performed in the remaining three patients. Thus, a total of 65 IMAs were depicted angiographically.

In all the 34 women, free flap breast reconstruction was performed unilaterally ($n = 28$) or bilaterally ($n = 6$). An in vivo assessment of the vessels at 21 previously irradiated internal mammary recipient sites and 19 previously nonirradiated recipient sites could be made by the surgeon performing the microsurgery.

For the histological assessment technically insufficient slides had to be excluded, leaving a total of 14 irradiated and 11 nonirradiated specimens of the IMAs and 27 nonirradiated specimens of the deep inferior epigastric arteries.

Results

Correlation between Internal Mammary Angiography and Previous Radiotherapy

The anatomy, course, and contrast-filling diameter of the IMA were scored as normal on 60 of the 65 angiographies. A total of 21 out of the 60 IMAs had previously received the full dose of radiation. Three of the five remaining arteries that were scored as angiographically aberrant had previously not been irradiated (►**Table 1**).

For just 40% of the angiographically aberrant arteries and 35% of the angiographically normal arteries had been irradiated, the authors conclude that radiation therapy does not correlate with angiographically obvious damage to the IMA ($p > 0.2$).

Correlation between Internal Mammary Angiography and Intraoperative Observations

Of the 40 arteries, that could be assessed intraoperatively, 37 did not show macroscopic changes of the vascular wall or diameter. In one of the remaining three cases there was an evident intraluminal plaque and in the other two there were mild fibrotic changes with increased stiffness of the arterial wall (►**Table 2**). There was no correlation between the preoperative angiographic findings and the intraoperative observations of the arteries ($p > 0.2$).

Table 1 Correlation between preoperative angiographic findings ($n = 65$) and parasternal irradiation therapy (number of aberrant angiographies per side)

Angiographic findings	Parasternal irradiation	No parasternal irradiation
Narrowing	0	3
Deviation of vessel course	2	0
Normal	21	39

Table 2 Comparison between intraoperative finding of the internal mammary artery and preoperative angiographic findings and preoperative parasternal irradiation therapy (number of reconstructed sides; $n = 40$)

Operative findings	Aberrant angiography	Normal angiography	Parasternal irradiation	No parasternal irradiation
Mild fibrosis IMA	1	1	1	1
Extended fibrosis IMA/ intraluminal plaque	0	1	0	1
Normal IMA	4	33	20	17

Abbreviation: IMA, internal mammary artery.

Correlation between Radiotherapy and Intraoperative Observations

The authors found no significant correlation between the intraoperative findings on the internal mammary vessels and exposure to previous radiation ($p > 0.2$). Arterial wall fibrosis was observed in one of the irradiated internal mammary vessels and two of the nonirradiated receptor arteries (►**Table 2**).

The IMVs showed a macroscopically normal vascular wall in 28 of the 40 recipient sites (►**Table 3**). Because of internal mammary venous insufficiency, the microsurgeons switched to using to the jugular vein ($n = 1$) or the cephalic vein ($n = 1$) for the venous anastomosis in 2 of the 12 cases, which exhibited abnormalities.

As for the arteries, there was no significant correlation ($p > 0.2$) between intraoperative venous macroscopical appearance and previous radiation exposure (►**Table 3**).

Comparison of Histological Vessel Measurements between Irradiated and Nonirradiated Arteries

There were no significant differences in mean "wall-to-lumen area ratio" between the irradiated IMA, nonirradiated IMA, and the inferior epigastric artery, and neither in their mean "media-to-lumen area ratio" (►**Table 4**). Comparing the media-to-lumen and the wall-to-lumen area ratio of irradiated and nonirradiated IMAs graphically (►**Fig. 1**), it was apparent that both ratios were nearly congruent in both groups. Of the three patients, who underwent bilateral breast reconstruction with just one of the IMAs being irradiated, no significant difference in wall-to-lumen area ratio could be found between the irradiated and the nonirradiated IMA.

Correlation between Internal Mammary Angiographic Findings and Outcome of Surgery

A total of 40 free flaps were transplanted in 34 patients. Overall 33 breast reconstructions were free of complications (►**Table 5**). There were seven postoperative flap complications, leading to complete flap loss in four of them (10%). Five of the seven complicated breast reconstructions were associated with a normal angiography. Hence, the preoperative angiographic findings did not correlate with the surgical outcome ($0.1 > p > 0.05$).

Table 3 Correlation between intraoperative finding of the internal mammary vein and preoperative parasternal irradiation therapy (number of reconstructed sides; $n = 40$)

Operative findings	Parasternal irradiation	No parasternal irradiation
Small diameter IMV	0	3
Brittle wall of IMV	4	2
Mild fibrosis IMV	1	2
Normal IMV	16	12

Abbreviation: IMV, internal mammary vein.

Table 4 Wall-to-lumen and media-to-lumen area ratios of irradiated ($n = 14$) and nonirradiated ($n = 11$) internal mammary arteries and the inferior epigastric arteries in the pedicle of the flaps ($n = 27$)

	Wall-to-lumen area ratio		Media-to-lumen area ratio	
	Mean	SD	Mean	SD
Irradiated IMA	2.12	0.88	1.99	0.80
Non-irradiated IMA	1.72	0.42	1.61	0.43
IEA of DIEP-flap	2.31	1.23	2.25	1.16

Abbreviations: DIEP, deep inferior epigastric perforator; IEA, inferior epigastric artery; IMA, internal mammary artery.

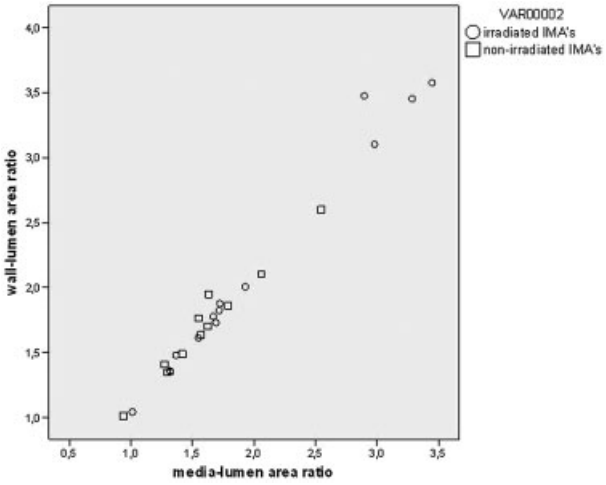

Fig. 1 Graph comparing media-lumen and wall-lumen area ratios of irradiated and nonirradiated internal mammary arteries.

Of those two patients with an aberrant angiography and a postoperative complication, one patient had a combined arterial and venous thrombosis resulted in total flap loss after revision. This patient had shown a medial deviation of the IMA on the preoperative angiography but intraoperative, macroscopic inspection of the internal mammary vessels had not revealed any vascular disorder. The other patient had a partial fat necrosis, while the preoperative angiography had shown a small lumen of the IMA but this could not be confirmed during surgery.

Correlation between Previous Radiotherapy and Outcome of Surgery

Total 17 of the 33 uneventful breast reconstructions and 4 of the 7 complicated breast reconstructions were in the group of previous radiotherapy to the internal mammary vessels (►**Table 5**). Hence, there was no statistical significant correlation between the two ($p > 0.2$).

Discussion

Even though irradiation may induce atherosclerotic narrowing in areas unusual for the natural occurrence of arterial disease,[12] only few authors studied the possible irradiation-related damage of the IMA as a source of free flap failure.[13] Likewise, reports on the outcome of IMA-grafts in cardiac revascularization surgery in patients with a history of thoracic radiation therapy are sparse. Some of these reports suggest that the irradiated IMA is unsuitable for cardiac grafting,[14,15] whereas other studies found no adverse effects on revascularization outcome.[16–18]

The authors found that internal mammary chain radiotherapy does not always cause angiographic or macroscopically obvious damage to the IMA. Furthermore, it was not possible to preoperatively predict postoperative complications on the basis of internal mammary angiography. Still, they found some correlation between previous radiotherapy and postoperative complications, but no significant or specific correlation between such irradiation and total flap loss.

Potential Shortcomings of this Study

As they only performed arterial angiographies, it was not possible to assess the IMVs preoperatively. To image the IMV an extra venography via the sternum or a computed tomography scan would have been necessary. To depict the veins the patients would have had to be exposed to extra radiation and the risk of complications.[19,20] Therefore, in their study a normal angiography does not rule out the possible surgical insufficiency of the IMV, which might be better depicted by duplex sonography.

Second, their series are too small to distinguish between short-term and long-term prevalence of radiation effects.

Last, they did not reckon with possible vascular damage induced by chemotherapy. Still, as 30 of their 34 patients (36 out of 40 flaps) were treated with chemotherapy before breast reconstruction no statistically significant observations could have been made from such data.

Table 5 Correlation between postoperative complications and preoperative angiographic findings and preoperative parasternal irradiation therapy (number of reconstructed sides, $n = 40$)

Postoperative complications	Aberrant angiography	Normal angiography	Parasternal irradiation	No parasternal irradiation
Venous thrombosis with successful reanastomosis	0	2	1	1
Venous thrombosis with unsuccessful reanastomosis and flap loss	0	2	1	1
Arterial and venous thrombosis with unsuccessful reanastomosis and flap loss	1	0	1	0
Too fragile vessels for anastomosis with flap loss	0	1	1	0
Partial fat necrosis	1	0	0	1
None	3	30	17	16

Quality of Internal Mammary Vessels

In nonirradiated IMAs atherosclerotic changes are rare. The incidence of artherosclerotic changes detected by angiography in literature ranges from 0 to 11.1%[21–25] and the incidence of histologically proven arterial stenosis has been found to vary from 4.2 to 12.4%.[26,27] Still, none of the 215 specimen of the study by Kay et al[26] and only one specimen in a series of 160 patients studied by Sisto and Isola[27] showed more than a 50% reduction in lumen diameter of the IMA.

Hardly any data are available on the incidence of atherosclerosis in series of irradiated IMAs. As such van Son et al. reported on four patients with radiation-induced coronary artery disease in whom internal mammary angiography was performed.[16] The angiography of the IMA was judged not patent in two patients and, in both, histological examination confirmed dense fibrosis of the IMA wall with complete obliteration of the lumen. The arteries of the other two patients showed a slightly thickened adventitia with minimal signs of fibrosis.

In this study, angiographic changes of the IMA wall have been found in five out of 65 angiographies (7.7%). Macroscopic changes of the IMA wall were intraoperatively observed in 3 out of 40 patients (7.5%). Compared with the literature both prevalence's are well within the normal range.[21–27]

Histology of Irradiation Damage

Gassman was the first to describe vascular lesions of radiodermatitis and noted the swelling and proliferation of the endothelium to the point of projection into the lumen of small arteries.[2] Irradiation may produce arterial damage varying from intimal thickening, fragmentation of the elastic lamina, over-production of elastic tissue, chronic inflammation, and necrosis of the adventitia, hyaline thickening, to thrombosis and the production of collagen in the larger arteries.[3–5]

Medium-sized arteries such as the IMA are less sensitive to irradiation than blood capillaries,[10,11] but these arteries may still show prominent adventitial fibrosis, subendothelial and intimal accumulation of foam cells, and hyaline deposition in the media as a result of irradiation.[10] Russell et al described an increase in proteoglycan content of the intima of irradiated IMA vessels compared with nonirradiated IMA, from 65 to 73%. However, the collagen content between irradiated an nonirradiated IMAs was not found to differ significantly.[9]

The authors were unable to find differences in wall-to-lumen area ratio, or media-to-lumen area ratio in the irradiated arteries and the nonirradiated arteries. Probably, the dose of radiation in their series was relatively low compared with the radiation sensitivity of the IMA; or the follow-up interval was too short. Still, linking the intraoperative observations on the IMVs with previous irradiation therapy, it was their impression that irradiated veins were a bit more brittle than nonirradiated veins.

Discussion of the Observations

The authors observed a low, statistically insignificant correlation between previous irradiation and surgical outcome. But there was no correlation between angiographic aberrances and surgical outcome. This may be explained, as flap survival is not only related to the quality of the IMA and IMV, but is influenced by many more factors, such as skills, technique, ischemia, perforator quality, and smoking habits of the patient. They found a slight predominance of macroscopically brittle walls among the previously irradiated IMVs. Other intraoperatively observed venous aberrances such as a smaller diameter or mild fibrosis did not correlate with previous radiotherapy.

Their series may be too small to allow a statistically warranted conclusion regarding the correlation between previous radiotherapy exposure of vessels and surgical outcome. Still, it offers a good impression of the lack of correlation between preoperative angiography, possible irradiation damage to the IMA, and the intraoperative finding.

Conclusion and Alternative Techniques of Vascular Evaluation

The authors conclude that there is no value of preoperative highly selective digital subtraction angiography in the assessment of the degree of radiation-induced arterial damage and that there is no correlation to the vascular damage found during the operation and with histology. Thus digital subtraction angiography is not helpful as a preoperative assessment tool for the selection of potential candidates for free flap mammary reconstruction. Furthermore, such angiography is expensive and invasive. Although its risk of complications is small, these risks are not negligible as they include, arterial aneurysm at the puncture side (0.4–2.0%), anaphylactic shock resulting from allergy to the contrast medium (0.2–0.4%), superficial phlebitis and edema (17.9%), renal impairment (< 2%), and hemorrhagic (11.4%) and thrombotic events (0–4.0%).[28–33] Due to these risks and as the authors found the subtraction angiography unhelpful, color flow Doppler sonography, computed tomography angiography, or magnetic resonance angiography might be better screening methods.[18,22,34,35]

Conflict of Interest

There are no potential or actual, personal, political, or financial interests by any of the authors in the material, information, or techniques described in the article.

References

1 Pomahac B, Recht A, May JW, Hergrueter CA, Slavin SA. New trends in breast cancer management: is the era of immediate breast reconstruction changing? Ann Surg 2006;244(2):282–288
2 Gassman A. Zur Histologie der Röntgenulcera. Fortschr Geb Roentgenstr 1899;2:199–207
3 Lindsay S, Kohn HI, Dakin RL, Jew J. Aortic arteriosclerosis in the dog after localized aortic x-irradiation. Circ Res 1962;10:51–60
4 Sams A. Histological changes in the larger blood vessels of the hind limb of the mouse after x–irradiation. Int J Radiat Biol Relat Stud Phys Chem Med 1965;9:165–174
5 Fonkalsrud EW, Sanchez M, Zerubavel R, Mahoney A. Serial changes in arterial structure following radiation therapy. Surg Gynecol Obstet 1977;145(3):395–400
6 Hoopes PJ, Gillette EL, Withrow SJ. Intraoperative irradiation of the canine abdominal aorta and vena cava. Int J Radiat Oncol Biol Phys 1987;13(5):715–722

7 Silverberg GD, Britt RH, Goffinet DR. Radiation-induced carotid artery disease. Cancer 1978;41(1):130–137
8 Moritz MW, Higgins RF, Jacobs JR. Duplex imaging and incidence of carotid radiation injury after high-dose radiotherapy for tumors of the head and neck. Arch Surg 1990;125(9):1181–1183
9 Russell NS, Hoving S, Heeneman S, et al. Novel insights into pathological changes in muscular arteries of radiotherapy patients. Radiother Oncol 2009;92(3):477–483
10 Chuang VP. Radiation-induced arteritis. Semin Roentgenol 1994; 29(1):64–69
11 Fajardo LF. The pathology of ionizing radiation as defined by morphologic patterns. Acta Oncol 2005;44(1):13–22
12 Nylander G, Pettersson F, Swedenborg J. Localized arterial occlusions in patients treated with pelvic field radiation for cancer. Cancer 1978;41(6):2158–2161
13 Tran NV, Chang DW, Gupta A, Kroll SS, Robb GL. Comparison of immediate and delayed free TRAM flap breast reconstruction in patients receiving postmastectomy radiation therapy. Plast Reconstr Surg 2001;108(1):78–82
14 Schulman HE, Korr KS, Myers TJ. Left internal thoracic artery graft occlusion following mediastinal radiation therapy. Chest 1994;105 (6):1881–1882
15 Renner SM, Massel D, Moon BC. Mediastinal irradiation: A risk factor for atherosclerosis of the internal thoracic arteries. Can J Cardiol 1999;15(5):597–600
16 van Son JAM, Noyez L, van Asten WNJC. Use of internal mammary artery in myocardial revascularization after mediastinal irradiation. J Thorac Cardiovasc Surg 1992;104(6):1539–1544
17 Gansera B, Haschemi A, Angelis I, et al. Cardiac surgery in patients with previous carcinoma of the breast and mediastinal irradiation: is the internal thoracic artery graft obsolete? Thorac Cardiovasc Surg 1999;47(6):376–380
18 Nasso G, Canosa C, De Filippo CM, et al. Thoracic radiation therapy and suitability of internal thoracic arteries for myocardial revascularization. Chest 2005;128(3):1587–1592
19 Chasen MH, Charnsangavej C. Venous chest anatomy: clinical implications. Eur J Radiol 1998;27(1):2–14
20 Chiappa S, Coopmans De Yoldi G, Magri M. Trans-sternal phlebography of the internal mammary veins. Am J Roentgenol Radium Ther Nucl Med 1960;83:320–334
21 Finci L, Meier B, Steffenino G, Doriot PA, Rutishauser W. Nonselective preoperative digital subtraction angiography of internal mammary arteries. Cathet Cardiovasc Diagn 1990;19(1): 13–16
22 Sons HJ, Marx R, Godehardt E, Lösse B, Kunert J, Bircks W. Duplex sonography of the internal thoracic artery. Preoperative assessment. J Thorac Cardiovasc Surg 1994;108(3):549–555
23 Sons HJ, Godehardt E, Kunert J, Lösse B, Bircks W. Internal thoracic artery: prevalence of atherosclerotic changes. J Thorac Cardiovasc Surg 1993;106(6):1192–1195
24 Ochi M, Yamauchi S, Yajima T, Bessho R, Tanaka S. The clinical significance of performing preoperative angiography of the internal thoracic artery in coronary artery bypass surgery. Surg Today 1998;28(5):503–508
25 Bauer EP, Bino MC, von Segesser LK, Laske A, Turina MI. Internal mammary artery anomalies. Thorac Cardiovasc Surg 1990;38 (5):312–315
26 Kay HR, Korns ME, Flemma RJ, Tector AJ, Lepley D Jr. Atherosclerosis of the internal mammary artery. Ann Thorac Surg 1976;21 (6):504–507
27 Sisto T, Isola J. Incidence of atherosclerosis in the internal mammary artery. Ann Thorac Surg 1989;47(6):884–886
28 Skinner JS, Jackson MJ, Gholkar A, Adams PC. Cortical blindness during left internal mammary angiography. Int J Cardiol 1995;52 (2):119–123
29 Feit A, Reddy CV, Cowley C, Ibrahim B, Zisbrod Z. Internal mammary artery angiography should be a routine component of diagnostic coronary angiography. Cathet Cardiovasc Diagn 1992;25(2):85–90
30 Agaba AE, Hardiment K, Burch N, Imray CH. An audit of vascular surgical intervention for complications of cardiovascular angiography in 2324 patients from a single center. Ann Vasc Surg 2004;18 (4):470–473
31 Saklayen MG, Gupta S, Suryaprasad A, Azmeh W. Incidence of atheroembolic renal failure after coronary angiography. A prospective study. Angiology 1997;48(7):609–613
32 Lensing AW, Prandoni P, Büller HR, Casara D, Cogo A, ten Cate JW. Lower extremity venography with iohexol: results and complications. Radiology 1990;177(2):503–505
33 AbuRahma AF, Powell M, Robinson PA. Prospective study of safety of lower extremity phlebography with nonionic contrast medium. Am J Surg 1996;171(2):255–260
34 Evans GRD, David CL, Loyer EM, et al. The long-term effects of internal mammary chain irradiation and its role in the vascular supply of the pedicled transverse rectus abdominis musculocutaneous flap breast reconstruction. Ann Plast Surg 1995;35(4):342–348
35 Glassberg RM, Sussman SKK, Glickstein MF. CT anatomy of the internal mammary vessels: importance in planning percutaneous transthoracic procedures. AJR Am J Roentgenol 1990;155(2):397–400