Ann Surg Oncol (2019) 26:3099–3108
https://doi.org/10.1245/s10434-019-07531-4

Annals of
SURGICAL ONCOLOGY
OFFICIAL JOURNAL OF THE SOCIETY OF SURGICAL ONCOLOGY

ORIGINAL ARTICLE – BREAST ONCOLOGY

A Randomized Prospective Trial of Supine MRI-Guided Versus Wire-Localized Lumpectomy for Breast Cancer

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ABSTRACT

Background. Wire-localized excision of non-palpable breast cancer is imprecise, resulting in positive margins 15–35% of the time.

Methods. Women with a confirmed diagnosis of non-palpable invasive breast cancer (IBC) or ductal carcinoma in situ (DCIS) were randomized to a new technique using preoperative supine magnetic resonance imaging (MRI) with intraoperative optical scanning and tracking (MRI group) or wire-localized (WL group) partial mastectomy. The main outcome measure was the positive margin rate.

Results. In this study, 138 patients were randomly assigned. Sixty-six percent had IBC and DCIS, 22% had IBC, and 12% had DCIS. There were no differences in patient or tumor characteristics between the groups. The proportion of patients with positive margins in the MRI-guided surgery group was half that observed in the WL group (12 vs. 23%; $p = 0.08$). The specimen volumes in the MRI and WL groups did not differ significantly (74 ± 33.9 mL vs. 69.8 ± 25.1 mL; $p = 0.45$). The pathologic tumor diameters were underestimated by 2 cm or more in 4% of the cases by MRI and in 9% of the cases by mammography. Positive margins were observed in 68% and 58% of the cases underestimated by 2 cm or more using MRI and mammography, respectively, and in 15% and 14% of the cases not underestimated using MRI and mammography, respectively.

Conclusions. A novel system using supine MRI images co-registered with intraoperative optical scanning and tracking enabled tumors to be resected with a trend toward a lower positive margin rate compared with wire-localized partial mastectomy. Margin positivity was more likely when imaging underestimated pathologic tumor size.

The goal of breast-conserving surgery (BCS) is to resect the tumor with a surrounding margin of tissue free of cancer and to minimize the volume of tissue removed, thereby preserving the overall shape and appearance of the breast. For invasive cancer, tumor resection with negative margins is sufficient to minimize local recurrence and constitutes the standard of care.[1] For ductal carcinoma in situ (DCIS), resection with margins of at least 1–2 mm is recommended.[2,3]

With widespread use of screening mammography, more than half of women with invasive cancer and nearly all women with DCIS have their tumors detected before they become clinically palpable.[4,5] For non-palpable lesions, localization of the tumor before BCS is needed. The standard localization technique is wire localization. The greatest limitation of wire localization is inaccuracy. Wire localization requires the surgeon to estimate the three-dimensional (3D) position of the cancer from two-dimensional mammography images. Randomized controlled trials have shown that wire-localized excision results in positive margins for 12–57% of patients.[6–16] Re-

First Received: 14 January 2019;
Published Online: 29 July 2019

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excision for positive margins is emotionally difficult for patients, increases the potential for complications from surgery, impairs cosmesis, and is expensive.[17,18]

Findings have shown breast MRI to be more sensitive than mammography or ultrasound for detection of invasive cancer and DCIS.[19–21] Breast cancer size, as determined by histopathology, also is more accurately defined by MRI than by mammography or ultrasound.[22–24] Despite this increased accuracy, use of pre-operative MRI with the patient in prone position has not been conclusively demonstrated to produce better short-term outcomes. Although a prospective randomized Swedish study did demonstrate significantly lower re-operation rates in the MRI group, the Comparative Effectiveness of MRI in Breast Cancer (COMICE) trial failed to show a decrease in the positive margin rate with the use of prone MRI.[25,26] This outcome is not surprising because the shape of the breast during prone MRI is radically different from its shape with the patient supine in the operating room. In contrast, supine MRI replicates the surgical position and has the potential to increase the precision of BCS.[8,27]

We recently developed a new method of MRI-guided BCS that incorporates preoperative supine MRI to define tumor extent and uses an intraoperative optical scan to co-register the MRI image to the breast position in the operating room.[28] This technique provides the surgeon with 3D views of tumor shape and position within the breast as it appears during surgery and, when combined with intraoperative tracking technology, localizes breast cancer as accurately as by palpation.[28] This report describes results from a randomized prospective trial comparing our preoperative supine MRI/intraoperative optical scanning and tracking technique with wire localization.

METHODS

This study (Clinical Trials.Gov #NCT01929395) was approved by the Dartmouth Committee for the Protection of Human Subjects. The eligible patients were women 18 years of age or older with a non-palpable invasive breast cancer or DCIS 1 cm in diameter or larger that enhanced on diagnostic prone MRI. The study exclusion criteria ruled out implanted electrical devices, gadolinium allergy, pregnancy, neoadjuvant systemic therapy, and multicentric breast cancer. All patients were treated by three surgeons at Dartmouth-Hitchcock Medical Center in Lebanon, NH, USA.

The consenting patients were randomized by the study coordinator on a 1:1 basis to wire localization (WL group) or preoperative supine MRI with intraoperative scanning and tracking (MRI group). Randomization was stratified by DCIS versus invasive cancer and based on computer-generated randomly permuted blocks with random block sizes to achieve approximate balance in the treatment groups.

The surgeon and patient were notified of the group assignment by the study coordinator. The patients in the WL group had a wire placed preoperatively in their breast under mammographic or ultrasound guidance and underwent wire-localized partial mastectomy. All the patients in both study groups had mammograms and prone MRIs, and these images were available to the surgeon.

Intervention Group: Preoperative Supine MRI and Intraoperative Optical Scanning and Tracking

On the day of surgery, the patients in the MRI group had six to eight fiducials placed on the breast surface in standardized locations and then underwent contrast-enhanced breast MRI in the supine position on either a Phillips 3T MRI scanner (Philips Healthcare, Andover, MA, USA) with circular coils or a Siemens 1.5 T scanner (MAGNETOM Area, Siemens Healthineers, Malvern, PA, USA) with a rectangular flex coil. A soft pad was placed on the sternum to support the rectangular flex coil. The pad was designed with cutouts for each breast, which minimized breast deformation.

The patients were positioned in the scanner with their ipsilateral arm parallel to their body. A pre-injection T1-weighted ultrafast gradient echo sequence was acquired to define the breast volume and tissue structures while a post-injection T1-weighted turbo gradient echo volume acquisition with fat saturation was used to determine tumor location and shape.

One of two study radiologists outlined the tumor edges on contiguous MRI slices. A 3D virtual model of the tumor, breast surface, and chest wall was constructed using the segmented models in the 3D Slicer (version 4.3.1, www.slicer.org) software.[29]

The patients were positioned on the operating room table in supine position. Their ipsilateral arm was placed on a board and extended laterally, with the axilla exposed. Next, MRI fiducial markers were removed, and optical markers were placed on the skin at the MRI fiducial sites. A fixed rigid body position indicator with optical markers (Northern Digital, Inc. Waterloo, ON, Canada) was positioned on the patient's sternum, providing a frame of reference for the Polaris optical tracking system (Northern Digital, Inc).

Optical scanning of the breast surface and sternum was performed with the Go!Scan 50 handheld structured light scanning system (Creaform, Levus, Quebec, Canada). The fiducial markers allowed rigid co-registration of the tumor and chest wall models and the intra-operative breast surface scan to a common coordinate system tracked by the

Polaris optical tracking system. Transformation matrices for the rigid registration were efficiently calculated using a singular value decomposition technique as outlined by Hill and Batchelor[30] and implemented in Matlab (MathWorks, Natick, MA, USA) programming language.

Once the supine MRI was registered to the intraoperative optical surface scan, an interactive 3D image of the tumor in the breast was displayed on a computer screen in the operating room using custom-developed visualization and navigation software written in Python (Python Software Foundation, Beaverton, OR, USA) and Matlab programming languages (Fig. 1). This image allowed the surgeon to see where the tumor came closest to the skin and to the chest wall (Fig. 1b). The closest distances, in millimeters, from tumor to skin and from tumor to chest wall were displayed. The image included a projection of the tumor edges to the virtual breast surface (Fig. 1a). The shortest distance from the center of the MRI-defined tumor mass to the skin surface was used to orient the tumor edge projection.

The Polaris tracking camera unit was positioned above the operating table within line-of-sight of the fixed rigid body position indicator. The tracker then was registered to the fixed rigid-body-position indicator, which enabled tracking of a handheld stylus probe (Northern Digital, Inc) in the common coordinate system. The surgeon passed the tracked stylus probe over the breast while viewing the onscreen images of the probe tip and virtual breast surface, tumor, and chest wall models to mark the projected edges of the tumor on the breast surface (Fig. 1c). The handheld probe also was used visually to determine the directional vector from the skin to the center of the MRI-defined tumor. The optical fiducials were removed, and the surgeon performed the partial mastectomy guided by the projected tumor edge markings on the breast surface, knowledge of the directional vector to the tumor center, the 3D tumor image on the computer screen, and the closest distances

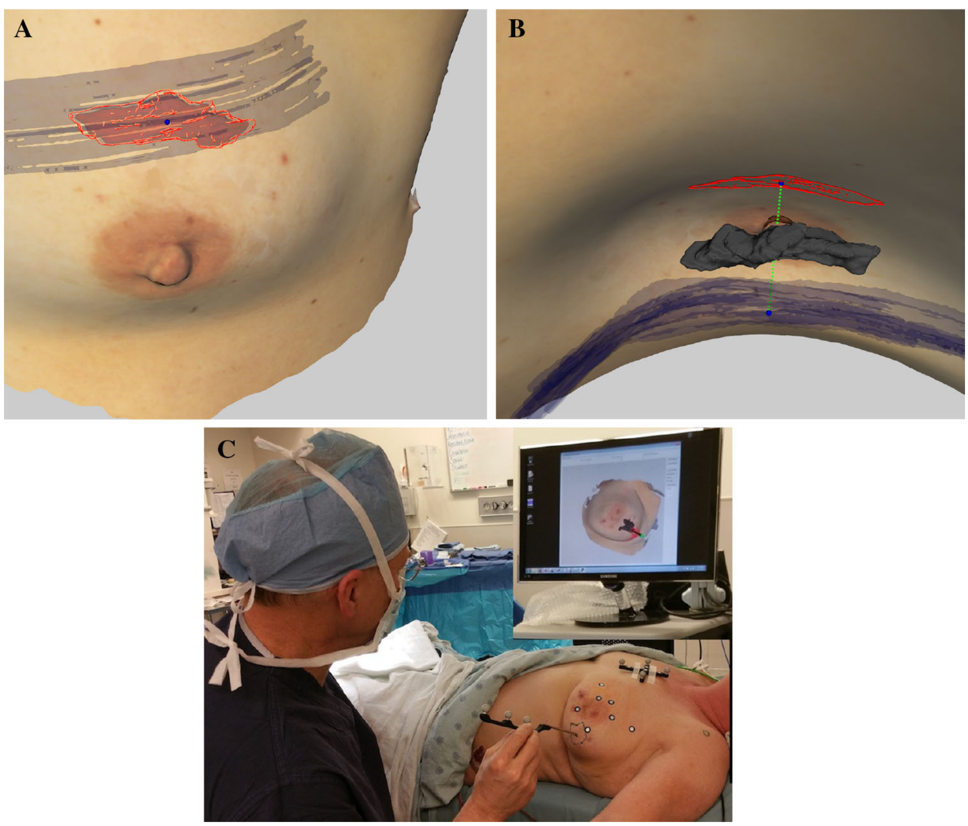


FIG. 1 **a** Intraoperative three-dimensional images showing the virtual projection of the tumor edges (red) to the breast surface. **b** View perpendicular to the breast surface. The tumor is the gray mass in the center. The chest wall surface is seen beneath the tumor, and the red lines are the tumor projection on the skin surface superficial to the tumor. The distances from the skin to tumor and tumor to chest wall are indicated by the green dotted lines. **c** Intraoperative tracking using a handheld probe to draw the projected tumor edges on the breast skin. The black and white dots on the breast are optical markers placed at the magnetic resonance imaging (MRI) fiducial sites. The handheld probe is represented by a virtual counterpart on the screen image. By placing the tip of the virtual probe on the virtual tumor edges, an outline of the tumor edges projected to the surface of the breast can be drawn (black). The handheld probe also was used for visual determination of the directional vector from the skin to the center of the MRI-defined tumor

from tumor to skin and chest wall determined from the co-registered supine MRI.

Primary and Secondary Outcome Measures

Specimens were placed in a graduated cylinder containing water to determine their volumes by displacement. Specimen margins were marked by the surgeon with six different colors of ink on a side table.[31] Mammograms were performed on all lumpectomy specimens. If intraoperative palpation or visual inspection raised a margin concern, or if the specimen mammogram suggested a close margin, additional selective shave margins were taken at the judgment of the surgeon. Shave margin volumes were determined by water displacement, and edges were inked by the surgeon.

The main outcome measure of the study was the positive margin rate. All specimens were reviewed by the designated study pathologist (W.A.W.) to determine whether a margin was positive or not. In the initial study design, margins for invasive cancers were considered positive if invasive cancer or DCIS cells were present at the edge (on ink) or if DCIS was present less than 1 mm from the inked edge. Margins for specimens that contained only DCIS were considered positive if DCIS was present less than 1 mm from the inked edge. If DCIS was less than 1 mm from the deep margin and the operative note clearly stated that the underlying fascia was removed from the muscle with the specimen, that margin was considered negative. We also calculated the proportion of patients with positive margins based on the consensus guidelines,[1,3] which was published after this study was initiated. The consensus guideline criteria denoting a positive margin for invasive cancer was invasive cancer or DCIS on ink. Margins for cases that contained only DCIS were considered positive if DCIS was present less than 2 mm from the inked edge.

Study sample size calculations were based on a retrospective analysis (performed by the study pathologist, W.A.W.) of margins from consecutive partial mastectomy specimens at our institution. In that analysis, 57 (32%) of 178 patients had positive margins. We considered a two thirds reduction in the positive margin rate (i.e., from 32% to $\leq$ 11%) to be clinically meaningful. The primary analysis was designed to compute the positive margin rate observed in the two groups and compare them using the Chi square test. Setting a significance level of 0.05 and a power of 80%, we determined that a sample size of 69 patients would be required in each group. The secondary outcome measures were assessed with a *t* test for continuous variables (e.g., specimen volumes) and a Chi square test for proportions.

RESULTS

Between 20 November 2014 and 27 March 2018, 138 patients were accrued to the study, with 69 patients assigned to each study arm. Of the 113 patients with invasive cancer shown on core biopsy, 56 were assigned to the MRI group and 57 to the WL group. Of the 25 patients with DCIS shown on core biopsy, 13 were assigned to the MRI group and 12 to the WL group. One patient with invasive breast cancer decided to have surgery at another institution after enrollment on study. All the remaining patients received the assigned treatment and were included in the analysis (Fig. 2). The study was stopped when it met the accrual goal of 138 patients.

As shown in Table 1, the baseline characteristics of the patients or tumors did not differ significantly between the two treatment groups. Of the invasive cancers in each group, approximately 85% were infiltrating ductal, 90% were estrogen receptor-positive, 5% were human epidermal growth factor receptor 2 (HER2)neu-positive, and 15% were node-positive. Notably, DCIS was identified in 75% of the invasive cancer specimens in both groups.

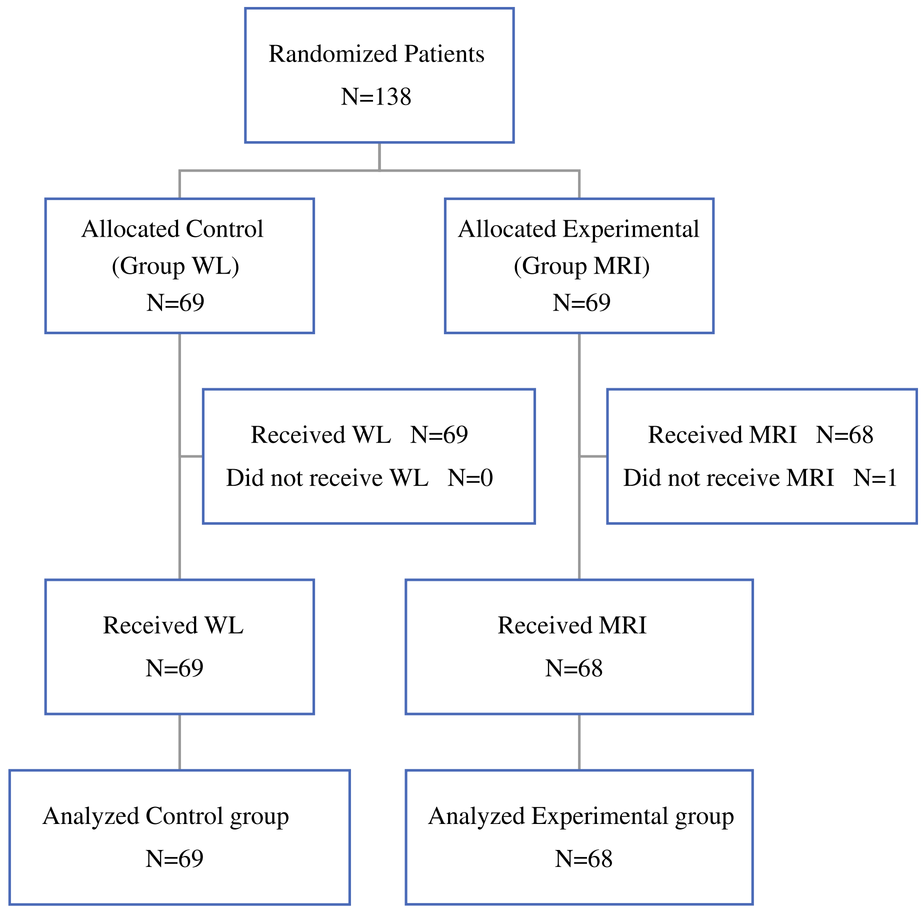
The tumor diameters (TDs), as measured by prone MRI, mammography, or ultrasound, were very similar in each group. The mean pathologic invasive TD was 1.39 ± 0.8 cm the MRI group and 1.51 ± 0.9 cm in the WL group ($p = 0.46$).

At the final pathology, approximately 10% of the patients in each group (7 in the MRI group and 9 in the WL group) had DCIS without invasive cancer. For 6 of the 13 patients in the MRI group and 3 of the 12 patients in the WL group who had only DCIS diagnosed with the core biopsy, invasive cancer was identified in the partial mastectomy specimen. Among the patients who had only DCIS in the partial mastectomy specimen, the mean pathologic DCIS TD was 1.91 ± 1.14 cm in MRI group and 2.23 ± 1.7 cm in WL group ($p = 0.7$).

The targeted cancer was excised at the time of initial surgery from 66 of the 67 patients (99%) in the MRI group. In one patient with a small cancer (pathologic diameter, 8 mm) deep in the upper outer quadrant of a large breast, the initial specimen mammography did not identify the marker clip or cancer. A supine MRI was performed, showing the tumor at the edge of the resection cavity, which was removed successfully by a second MRI-guided surgery. This patient was considered to have a positive margin.

All the patients in the WL group had their cancer excised at the time of their initial surgery. The proportion of patients who had additional shave margins taken at the time of partial mastectomy did not differ between the two groups (37% in the MRI group vs. 30% in the WL group; $p = 0.43$).

FIG. 2 Consort diagram



Positive Margin Rate

The proportion of patients with positive margins based on the study criteria was 12% (8/68) in the MRI group and 23% (16/69) in the WL group (p = 0.08) (Table 2). In the MRI group, 8 (13%) of 61 patients with invasive cancer and none (0%) of 7 patients with DCIS had positive margins. In the WL group, 15 (25%) of 60 patients with invasive cancer and 1 (11%) of 9 patients with DCIS had positive margins. Among the patients with invasive cancer in the MRI group, invasive cancer was found at the margin in four patients, DCIS was present at the margin in two patients, and DCIS was less than 1 mm from the margin in two patients. Among the patients with invasive cancer in the WL group, invasive cancer was present at the margin in five patients, DCIS was found at the margin in five patients, and DCIS was less than 1 mm from the margin in five patients.

The proportion of patients with positive margins based on the consensus criteria was 9% (6/68) in the MRI group and 19% (13/69) in the WL group (p = 0.09). In the MRI group, 6 (10%) of 61 patients with invasive cancer and none (0%) of 7 patients with DCIS had positive margins. In the WL group, 10 (17%) of 60 patients with invasive cancer and 3 (33%) of 9 patients with DCIS had positive margins (Table 2).

All eight of the patients in the MRI group with positive margins underwent re-excision. Cancer was found in the re-excision specimen from 4 (50%) of 8 patients. Of the 16 patients in the WL group, 15 underwent re-excision. Cancer was found in the re-excision specimen from 5 (33%) of the 15 patients.

The distribution of positive margins in the MRI and WL groups respectively were as follows: medial (19% and 15%), lateral (25% and 3%), cranial (12% and 7%), caudal (25% and 45%), superficial (6% and 15%), and deep (12% and 15%).

Specimen Volumes

The mean specimen volumes in the MRI and WL groups did not differ significantly (74 ± 33.9 vs. 69.8 ± 25.1 mL; p = 0.45; Fig. 3a). The median specimen volume in the MRI group was 70 mL (intraquartile range [IQR],

TABLE 1 Patient characteristics

	MRI	Wire localization	*p* value
No of patients	68	69	
Mean age (years)	63.6	64.0	0.8
Pathology core biopsy			
Invasive	55	57	
DCIS	13	12	
Final pathology			
Invasive	61	60	
Ductal	48	51	
Lobular	11	9	
Other	2	0	
DCIS	7	9	
DCIS present in invasive cancer (%)	75	76	
Tumor diameter imaging (cm)			
Prone MRI	2.14 ± 1.2	2.08 ± 1.1	0.8
Mammogram	1.43 ± 0.8	1.42 ± 0.9	0.99
US	1.22 ± 0.6	1.18 ± 0.4	0.71
Tumor diameter pathology (cm)			
Invasive	1.39 ± 0.8	1.51 ± 0.9	0.46
DCIS	1.91 ± 1.14	2.23 ± 1.7	0.7
Shave margin taken (%)	37	30	0.43
Estrogen receptor positive (%)			
Invasive	97	85	0.06
DCIS	71	100	0.16
HER2-positive (%)	3	8	0.25
Node positive (%)	10	15	0.47

MRI magnetic resonance imaging, *DCIS* ductal carcinoma in situ, *US* ultrasound, *HER2* human epidermal growth factor receptor 2

TABLE 2 Positive margin rates

	MRI			Wire localization			*p* value
	n	Positive	% positive	*n*	Positive	% positive	
A (Study Criteria)							
Invasive cancer	61	8	13	60	15	25	
DCIS	7	0	0	9	1	11	
Total	68	8	12	69	16	23	0.08
B (Consensus Criteria)							
Invasive cancer	61	6	10	60	10	17	
DCIS	7	0	0	9	3	33	
Total	68	6	9	69	13	19	0.09

A By study criteria: invasive cancer is positive if invasive cancer or DCIS is seen on ink or DCIS is less than 1 mm from ink; DCIS is positive if it is less than 1 mm from ink. B By consensus criteria[1,3]: invasive cancer is positive if invasive cancer or DCIS is seen on ink; DCIS is positive if it is less than 2 mm from ink

MRI magnetic resonance imaging, *DCIS* ductal carcinoma in situ

50–90 mL; range, 30–135 mL), whereas in the WL group, it was 70 mL (IQR, 50–85 mL; range, 20–120 mL; Fig. 3b).

For the patients in the MRI group, we calculated an "ideal" specimen volume by adding 1 cm in all dimensions to the 3D tumor image generated from the supine MRI images. The mean ideal specimen volume calculated

TABLE 3 Relationship between tumor diameter on imaging versus pathology and likelihood of positive margins

Imaging versus pathology	Imaging method	
	Prone MRI *n* (%)	Mammogram *n* (%)
A		
Imaging underestimated by > 2 cm	6 (4)	12 (9)
Imaging underestimated by > 1 cm	10 (7)	20 (15)
Imaging within 1 cm	101 (74)	107 (78)
Imaging overestimated by > 1 cm	26 (19)	10 (7)
Imaging overestimated by > 2 cm	8 (6)	3 (2)
B		
	Cases with positive margins (%)	
Imaging underestimated by > 2 cm	67	58
Imaging underestimated by > 1 cm	40	50
Imaging within 1 cm	18	12
Imaging overestimated by > 1 cm	8	10
Imaging overestimated by > 2 cm	0	0

A Relationship between tumor diameter on imaging and pathology. The number in the table indicates the number of patients in that category. For example, in 6 patients, the tumor diameter on prone MRI underestimated the diameter on pathology by more than 2 cm. This represents 4% of the total number of study patients. B Likelihood of positive margins. The value in the table is the percentage of cases in each category that had positive margins (n = 137 cases)

MRI magnetic resonance imaging

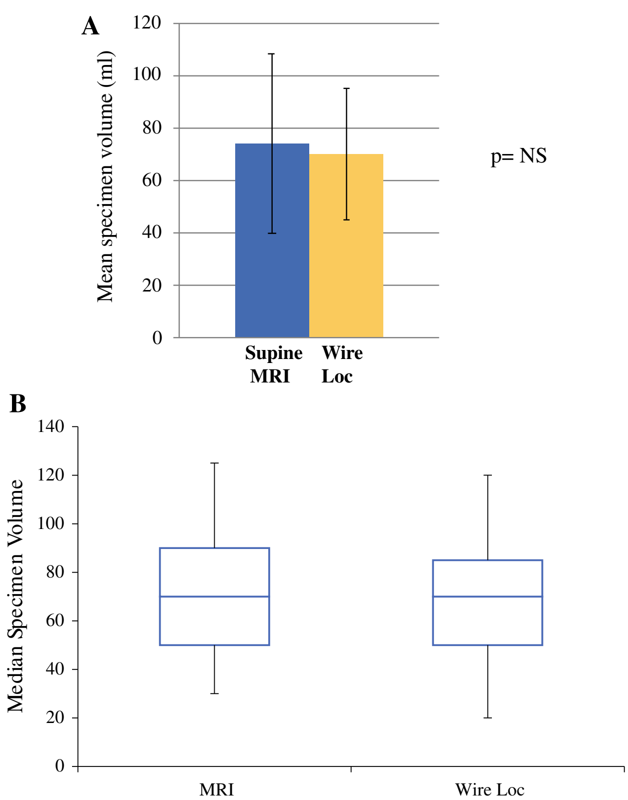


FIG. 3 Specimen volumes. **a** Mean ± standard deviation specimen volumes for the magnetic resonance imaging (MRI) and wire-localized (WL) groups. **b** Median (range) and intraquartile range of specimen volumes for the MRI and WL groups

only for the MRI group by adding 1 cm to all surfaces in the virtual three-dimensional model was 45.2 ± 24.6 mL.

Relationship Between Tumor Diameter on Imaging and Pathology

We compared TDs on prone MRI and mammography with TD measured histologically for all 137 study patients. The TD was underestimated by 2 cm or more in 4% (6/137) of the cases using MRI versus 9% (12/137) of the cases using mammography. The TD was underestimated by 1 cm or more in 7% (10/137) of the cases using MRI and in 15% (20/137) of the cases using mammography. In approximately 75% of the cases, the TD using MRI or mammography was within 1 cm of the pathologic diameter. Using MRI, the pathologic TD was overestimated by 1 cm or more in 19% of the cases and by 2 cm or more in 6% of the cases. Mammography overestimated the pathologic TD by 1 cm or more in 7% of the cases and by 2 cm or more in 2% of the cases (Table 3).

Specimen margins were more likely to be positive when TD was underestimated by imaging. Using MRI, the tumor margin was positive in 67% (4/6) of the cases when TD was underestimated by 2 cm or more, and in 40% (4/10) of the cases when TD was underestimated by 1 cm or more. In contrast, margins were positive in 18% of the cases when MRI imaging was within 1 cm of the pathologic diameter, in 8% of the cases when MRI overestimated TD by 1 cm or more, and in no cases when MRI overestimated TD by 2 cm or more. Margins were more likely to be positive when the TD was underestimated by 2 cm or more than when it was underestimated by less than 2 cm (4/6 [67%] vs. 20/131 [15%]; $p = 0.0012$). Further analysis of the six cases with TD underestimated by 2 cm or more using MRI showed that four of the cases had small infiltrating ductal carcinomas with a large component of DCIS, whereas two of the cases had infiltrating lobular carcinomas.

Using mammography, the tumor margin was positive in 58% (7/12) of the cases when TD was underestimated by 2 cm or more, and in 50% (10/20) of the cases when TD was underestimated by 1 cm or more. In contrast, margins were positive in 12% of the cases when mammographic imaging was within 1 cm of the pathologic TD, 10% of the cases when mammography overestimated TD 1 cm or more, and in no cases when mammography overestimated TD by 2 cm or more. Margins were more likely to be positive when TD was underestimated by 2 cm or more versus when it was underestimated by less than 2 cm (7/12 [58%] vs. 17/125 [14%]; $p < 0.0001$).

DISCUSSION

This study was the first to demonstrate that supine MRI can be used to guide breast-conserving excisions of nonpalpable invasive breast cancer. Using the image-guidance technique described in this report, the positive margin rate was cut in half, from 23% with wire-localized partial mastectomy to 12% with supine MRI-guided surgery. In retrospect, our study was underpowered to demonstrate that this magnitude of decrease achieved statistical significance. Our pre-study power calculations, based on positive margin rates from cases managed at our institution (and consistent with published positivity rates), assumed a higher positive margin rate (32%) in the WL study arm. Although we achieved our hypothesized positive margin rate in the experimental (supine MRI) study arm, the lower than expected positive margin rate in the control group yielded a p value of 0.08.

Placing our WL group findings in the context of 11 other randomized controlled trials (RCTs) of wire-localized partial mastectomy is instructive.[6–16] In these studies, positive margin rates varied from 12 to 57% and appear to have been influenced by several factors including tumor size, volume of tissue removed, and definition of a positive margin. Relative to other RCTs, the positive margin rate we observed in our WL group was lower than expected. For example, compared with the Chapgar et al.[14] study, which used the same definition of a positive margin and had similar specimen volumes, our positive margin rate was lower (23 vs. 34%) despite the substantially larger tumors in our study (median diameter, 17 vs 11 mm).

The RCT results also put the findings from our MRI-guided partial mastectomy group into perspective. With this new guidance technique, we achieved a positive margin rate of 12%, comparable with the three lowest rates observed in previously reported RCTs analyzing wire localization of invasive cancers.[10,15,16] Furthermore, the low rate was accomplished in cases that involved substantially larger tumors than those in the Bloomquist et al.[15] and Langhans et al.[16] studies (median TD, 16 vs 10 and 9 mm, respectively), and that had much lower specimen volumes than in the Lovrics et al.[10] study (70 vs. 183 mL, respectively). Using the new consensus definition of positive margins, the positive margin rate in our experimental group (9%) was lower than those reported in any previously published RCT.

The positive margin rate was lower when we used the new consensus guidelines versus our study definition in the WL group (19 vs. 23%) and in the MRI group (9 vs. 12%). Notably, whether our study definition or the new consensus guideline was used, the positive margin rate in the MRI group was half the rate in the WL group.

Surgeon bias is a potential limitation of any randomized trial that does not have blinded treatment arms. For example, surgeons may have more frequently performed selective margin shave biopsies at the time of the initial tumor excision (which were governed by the surgeon's subjective judgment regarding the adequacy of the initial excision) in one group. Such bias does not appear to have occurred in the current trial. No significant difference was found in the proportion of patients who had selective shave margins taken between the MRI group (37%) and the WL group (30%) (Table 1).

A recent retrospective study of 3391 patients with invasive cancer and 727 patients with DCIS who underwent wire-localized partial mastectomy showed that re-excision for positive margins is much more common among patients with DCIS (37%) than among patients with invasive cancer (13%) (odds ratio [OR], 3.82; 95% confidence interval [CI], 3.19–4.58).[32] Thus, innovative trials of alternative methods for better localization and excision of DCIS are essential. Sakakibara et al.[8] compared wire-localized partial mastectomy with supine MRI-guided partial mastectomy for patients with small foci of DCIS and found that the positive margin rate in the wire-localization group was 39% versus only 12% in the supine MRI-guided group, and that the specimen volumes were smaller.

Both the Sakakibara et al.[8] trial and our study demonstrate that supine MRI-guided surgery has the potential to increase the precision of BCS. Sakakibara et al.[8] overlaid the maximal intensity projection (MIP) MRI image of

DCIS onto transparent sheets and then used linac-imaged instruments to reproduce the extent of DCIS on the breast surface.[8] Our method is inherently different. Using our 3D-image co-registered/intraoperative tracking technique, the surgeons have all they need for precise excision of the cancer including knowledge of the distance from the cancer to skin and chest wall, tumor shape, and location of the tumor edges. The limitations of the technique we have described include the need for technical support in the operating room and the challenge of remembering the directional vector from the skin surface to the center of the MRI-defined tumor.

Previous studies have shown that MRI more accurately defines tumor size than mammography or ultrasound.[22–25] Boetes et al.[23] evaluated 60 breast cancers. In only one patient (2%) was the pathologic TD more than 2 cm larger than the diameter shown on MRI. In another study, 2 of 68 patients (3%) had pathologic diameters more than 2 cm larger than the diameter shown on MRI.[22] Our results are consistent with these findings. We observed that MRI underestimated TD by 2 cm or more in only 4% of patients. We found that MRI was substantially better than mammography, which underestimated TD by 2 cm or more in 9% of patients. This result is an important potential advantage of supine MRI used to guide surgery because we have shown that underestimation of TD is associated with a higher percentage of positive margins.

In summary, we have shown that a novel image-guidance system based on supine MRI and intraoperative optical scanning and tracking enabled non-palpable breast cancer to be resected with volumes equivalent to those of wire-localized partial mastectomy. The patients who had supine MRI-guided surgery showed a trend toward a lower positive margin rate. Further study of supine MRI-guided partial mastectomy for non-palpable invasive breast cancer and DCIS is warranted.

ACKNOWLEDGMENT This study was supported by NIH/NCI Grant R21 CA182956-01 to Dr. Richard J. Barth Jr.

CONFLICT OF INTEREST Drs. Barth, Krishnaswamy, and Paulsen have ownership interest in CairnSurgical Inc.

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