Prone liver phase MRA demonstrates improved intramuscular vascular detail compared to CTA in preoperative perforator mapping for free autologous abdominally-based breast reconstruction

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Background: MRA and CTA are both used to evaluate perforator anatomy in preparation for autologous breast reconstruction. While CTA is most commonly performed, prone liver phase MRA (PLP-MRA) can be performed concomitantly with breast MRI to assess arterial and venous anatomy while providing superior discrimination of vascular anatomy.

Methods: Consecutive patients with planned free autologous abdominally-based breast reconstruction were prospectively randomized to undergo preoperative perforator mapping with CTA or PLP-MRA. Imaging was used to predict whether a deep inferior epigastric artery perforator flap (DIEP) or muscle-sparing-2-TRAM (MS2-TRAM) would be performed. Paired radiographic and blinded intra-operative measurements of perforator location relative to the umbilicus, intramuscular pedicle length and pedicle position relative to the semilunar line were compared by paired Wilcoxon rank sum test.

Results: The type of flap performed was accurately predicted in all cases from PLP-MRA or CTA. Both PLP-MRA and CTA accurately predicted perforator location (48 hemi-abdomens) and distance from semi-lunar line (30 hemi-abdomens). PLP-MRA was superior to CTA in accurately predicting intra-muscular pedicle length ($P<0.05$). PLP-MRA allowed venous and arterial contrast to be separately identified in perforators >2 mm in diameter.

Conclusions: PLP-MRA offers superior accuracy in predicting intramuscular pedicle length compared to CTA while maintaining accuracy in determining perforator location and pedicle position to assist with flap design. This PLP-MRA protocol can be performed concomitantly with pre-operative breast MRI in select patients to avoid multiple imaging modalities and avoid radiation exposure.

Keywords: Microsurgery; CTA; MRA; perforator; preoperative planning; surgical planning; virtual surgery; breast reconstruction; free flap

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Introduction

Free autologous abdominally-based breast reconstruction is a reliable technique for producing a natural result after mastectomy by restoring soft tissue volume and contour while reconstituting the skin envelope of the breast. Compared to the free transverse rectus abdominis myocutaneous (TRAM) flap, the deep inferior epigastric artery perforator (DIEP) flap or muscle-sparing flaps are advantageous because of decreased abdominal morbidity. However, there is an increased risk of fat necrosis and partial flap loss (1-4). As muscle-sparing and perforator flap techniques have evolved, radiographic imaging has been used to pre-operatively design flaps based on a patient's unique anatomy with the goal of decreasing operative time and minimizing complications (2,5).

CTA, MRA, and Doppler sonography have been used for pre-operative planning of free flap harvest for breast reconstruction and have been shown to reliably predict abdominal wall anatomy (5-11). Preoperative imaging is commonly used to facilitate planning and execution of abdominal perforator flap harvest by demonstrating cutaneous perforator location and deep inferior epigastric or superficial inferior epigastric artery dominance and branching pattern. Pre-operative imaging facilitates flap dissection and allows the surgeon to provide personalized informed consent by understanding the suitability of the patient's vascular anatomy before surgery (8,12-14). CTA and MRA are most commonly employed for pre-operative planning due to their reliability and availability, whereas Doppler ultrasonography performance can suffer from technician variability (6,7).

Prone liver phase MRA (PLP-MRA) is a 3D volumetric fat-suppressed gradient echo technique that has been shown to have superior muscle to vascular detail compared to CTA (15-17). The liver phase MRA protocol allows combined arterial and venous detail (*Figure 1*), with markedly enhanced contrast between the vessels and surrounding muscles compared to CTA (15). Additionally, it does not expose the patient to ionizing radiation. The simultaneous enhancement of perforating arteries and their paired veins with MRA enables better selection of optimal perforators (17). Both 1.5-T and 3.0-T MRI scanners can be used for this purpose, but 1.5-T is preferred due to less suppression of the surrounding muscle, leading to enhancement of the relationship between perforators and muscle (16).

Pre-operative imaging to plan flap-based reconstruction is often scheduled after consultation for breast reconstruction, in addition to other imaging studies such as breast MRI or PET CT, which are used for staging (18-20). PLP-MRA can be performed concomitantly with breast MRI. It is available in many tertiary care centers, allowing for preoperative planning for flap selection during the breast cancer workup. Furthermore, it has the potential to improve convenience in appropriately selected patients by minimizing the number of imaging modalities employed in their treatment.

With CTA having widespread use in operative planning of free autologous abdominally-based breast reconstruction, this modality was selected as the comparison for PLP-MRA to study its performance in evaluating abdominal wall vascular anatomy (12).

Methods

Imaging modality selection

Informed consent documentation was obtained from each patient prior to participation based on a protocol approved by the Institutional Review Board at Virginia Commonwealth University (IRB #13438). Twenty-four consecutive patients electing to proceed with free autologous abdominally-based breast reconstruction were randomized to receive PLP-MRA or CTA using a random number generator with the code protected by the radiographic study interpreter (Randomness and Integrity Services, Ltd. Dublin, Ireland). Patients were randomized to either PLP-MRA or CTA (as opposed to obtaining both studies) due to the need to obtain insurance authorization for the imaging. Any female patient with a desire to undergo breast reconstruction was eligible for inclusion regardless of the need for delayed or immediate reconstruction. Patients with an indwelling vascular access device or breast tissue expander were excluded from the study due to the inability to randomize these patients to PLP-MRA. Age, BMI, smoking status, prior medical conditions, and prior abdominal surgery were compared to ensure the fidelity of the randomization. Medical conditions recorded in this study include diabetes, hypertension, and history of coronary artery disease. All patients in this study had a minimum of one-year follow-up.

Radiographic outcome variables

CTA and PLP-MRA imaging were used to predict whether

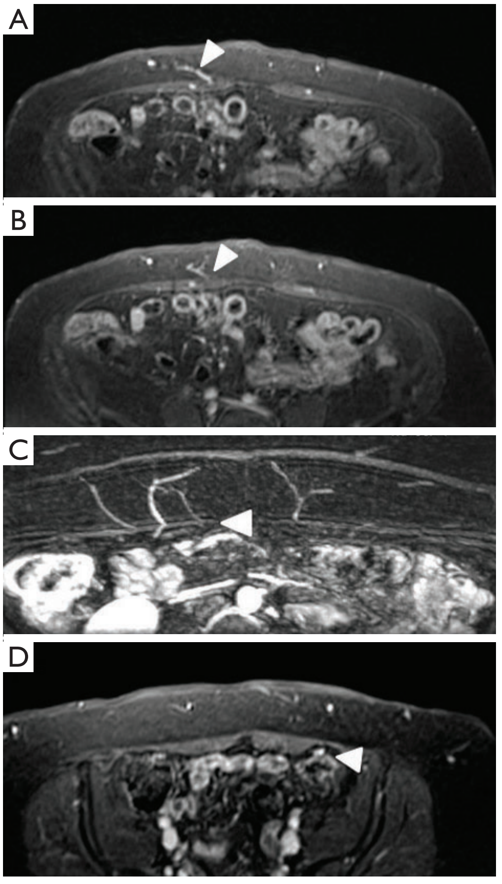

Figure 1 PLP-MRA vascular anatomy analysis. PLP-MRA image demonstrating (A) arterial and (B) venous components of single perforator due to the liver phase of the exam; (C) subcutaneous perforator branching showing excellent discrimination between fat and perforating vessels; (D) PLP-MRA image showing ease of vascular-muscular discrimination with pedicle beneath rectus muscle in this image. All vessels of interest marked with an arrowhead. PLP-MRA, prone liver phase MRA.

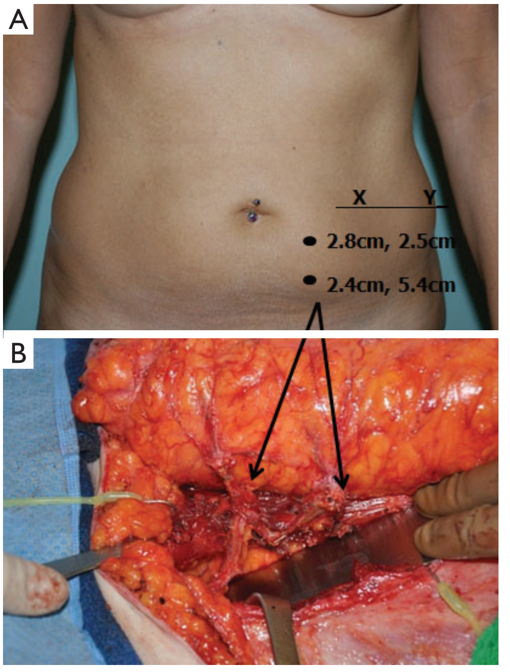

Figure 2 Perforator location relative to umbilicus. PLP-MRA patient number 3 with (A) skin marking perforator location relative to umbilicus based on MRA data and (B) Intra-operative correlation. PLP-MRA, prone liver phase MRA.

a DIEP or muscle-sparing free TRAM flap would be performed according to the senior author's interpretation of the studies. Briefly, dominant perforators greater than 1.5 mm in diameter were identified. If they were aligned vertically where rectus muscle sacrifice for dissection was not required, a DIEP flap was predicted. If there were no decidedly dominant perforators, or if perforator dominance appeared to be shared equally between medial and lateral systems, a muscle-sparing-2-TRAM (MS2-TRAM) free flap was predicted. The senior author devised this classification system to be utilized preoperatively by the co-authors, but he was blinded to both the scans (CTA and PLP-MRA) and their interpretation until completion of the operation.

Location of the cutaneous perforators relative to the umbilicus on CTA or PLP-MRA was correlated with intra-operative findings for all patients (*Figure 2*). The intramuscular pedicle length on pre-operative imaging was measured to determine the amount of muscular dissection that would be required for perforator flap dissection. For patients that underwent DIEP flap dissection, this distance was compared to the intraoperatively-measured intramuscular pedicle distance (*Figure 3*). The distance of the pedicle from the semilunar line at the most proximal and distal perforator was measured pre-operatively to help determine where the rectus sheath should be divided to initiate MS-2-TRAM free flap harvest. For patients undergoing MS-2-TRAM flap harvest, this distance was compared to intra-operative measurements at the most proximal and distal perforators, and both distances were averaged for imaging-derived and surgical-derived values separately (*Figure 4*). All radiographic endpoints were measured in a blinded manner with one study author determining the perforator location in each imaging study and the senior author recording perforator location

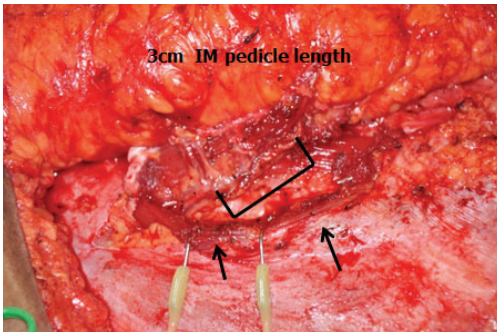

Figure 3 Intramuscular pedicle length. PLP-MRA patient number 7 with 3 cm intramuscular pedicle length as predicted by PLP-MRA. PLP-MRA, prone liver phase MRA.

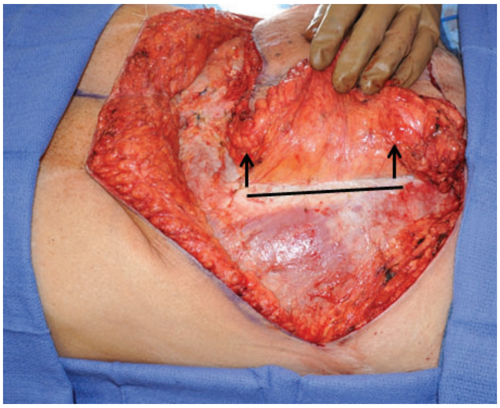

Figure 4 Pedicle distance from semi-lunar line. Demonstration of semilunar line measurement before operative pedicle dissection. The distance from the semilunar line to the lateral row perforators was recorded, fascia divided and then pedicle location identified relative to semi-lunar line. In practice, reliable pedicle position relative to semilunar line could accelerate MS-2-TRAM dissection. MS2-TRAM, muscle-sparing-2-transverse rectus abdominis myocutaneous.

intra-operatively. *Table 1* describes radiographic outcome measures and the potential impact on free flap design.

Statistics

Age and BMI between the two groups were compared using *t*-test, and medical/surgical history was compared between the two groups using Fisher's exact test to confirm randomization across all patient attributes.

Paired radiographic and intra-operative measurements of perforator location relative to the umbilicus, intramuscular pedicle length, and pedicle position relative to the semilunar line were compared by paired Wilcoxon rank sum test.

An effect size of one-centimeter difference in a single direction between radiographic and intra-operative assessment was selected for power calculation based on a surgeon focus group consensus of an important clinical difference. Power calculation for perforator location was determined with standard deviations taken from the literature using CTA and MRA (5,9,13-15,21,22). For distance from the semilunar line and intra-muscular pedicle length, thirty CTAs of the abdomen not included in this study were reviewed to provide a radiographic standard deviation for these variables to calculate paired sample size needed. Thirty-four perforators, 24 pedicle lengths, and 10 pedicle distances from the semilunar line would be required to provide 80% power to detect a 1-cm difference in radiographic versus intra-operative assessments with a P value of 0.05. Randomization was terminated when the appropriate number of radiographic outcomes was accumulated to power the study (21,23).

Results

A total of 24 patients were randomized to preoperative

Table 1 Radiographic variables and their use in surgical planning of free autologous abdominally-based breast reconstruction

Measurement	Application
Perforator location relative to the umbilicus	Perforators >1.5 mm in diameter are identified. Their location relative to the umbilicus provides information regarding the site of meticulous perforator dissection. Perforator identification helps to distinguish medial from lateral row dominance and DIEP flap versus MS-2-TRAM free flap candidates
Intramuscular pedicle length	Abdominal anatomy with short intra-muscular pedicle length requires less intra-muscular dissection and may be more appropriate for DIEP flap harvest compared to vessels requiring a significant length of intra-muscular dissection
Distance of pedicle from semilunar line	Position of lateral fascial incision for MS-2-TRAM flap harvest and knowledge of locations requiring meticulous dissection for muscle division based on pedicle location

Table 2 Distribution of imaging studies and flap types. Twenty-four patients randomized to PLP-MRA or CTA. Type I–III inferior epigastric branching patterns listed on y-axis. Flap selection based on perforator dominance and location listed beneath table

Variables	Randomized imaging type			
	PLP-MRA (n=12)		CTA (n=12)	
Branching pattern				
I	3	2	5	2
II	1	7	2	7
III	1	0	0	0
Flap type	5 (DIEP)	9 (MS-2-TRAM)	7 (DIEP)	9 (MS-2-TRAM)

DIEP, deep inferior epigastric artery perforator; MS2-TRAM, muscle-sparing-2-transverse rectus abdominis myocutaneous.

Table 3 Patient demographics and comorbidities. Age, BMI and medical and surgical comorbidities were compared to confirm fidelity of randomization. No difference was found for patient age, prior medical conditions or abdominal surgery between treatment groups

Imaging type	MRA	CTA	P
Demographics			
Age	47 [39–51]	49 [40–61]	0.82
BMI	31 [23–45]	29 [19–39]	0.60
Medical history			
Medical comorbidities	3	4	0.24
Prior abdominal surgery	4	5	0.40
Smoking	3	4	0.24

imaging by CTA (12) or PLP-MRA (12) with a total of 30 flaps (6 patients were bilateral). In the PLP-MRA group, 5 patients received DIEP flaps and 9 patients received MS2-TRAM flaps. In the CTA group, 7 patients received DIEP flaps and 9 patients received MS2-TRAM flaps (*Table 2*).

The mean ages were 47 [39–51] in the PLP-MRA group and 49 [40–61] in the CTA group. The mean BMI was 31 [23–45] in the PLP-MRA group and 29 [19–39] in the CTA group. There were 3 patients with medical comorbidities in the PLP-MRA group (2 with diabetes and 1 with hypertension) versus 4 patients in the CTA group (2 with hypertension, 1 with diabetes, and 1 with coronary artery disease and hypertension). Four patients in the PLP-MRA group had a history of abdominal surgery versus 5 patients

Table 4 Difference in measured perforator location between radiographic imaging study and intra-operative assessment for PLP-MRA and CTA. Both PLP-MRA and CTA accurately predicted perforator location when compared to intra-operative assessment. Perforators were included with diameter >1.5 mm on radiographic exam

Variables	Mean difference (range), cm	P
PLP-MRA (n=47)		
x-coordinates	0.78 (0–1.3)	0.62
y-coordinates	0.80 (0–2.4)	0.08
CTA (n=50)		
x-coordinates	0.69 (0–1.2)	0.30
y-coordinates	0.82 (0–2.2)	0.20

in the CTA group. There were 3 smokers in the MRA group and 4 smokers in the CTA group (*Table 3*).

Radiographic and intra-operative perforator locations differed in the PLP-MRA group by a mean of 0.78 cm (0–1.3 cm) on the x-axis (P=0.62) and by 0.80 cm (0–2.4 cm) on the y-axis (P=0.08) and in the CTA group by 0.69 cm (0–1.2 cm) on the x-axis (P=0.30) and by 0.82 cm (0–2.2 cm) on the y-axis (P=0.20). Both CTA and PLP-MRA accurately predicted perforator location with no significant differences between radiographic or intra-operative assessment. Forty-seven perforators greater than 1.5 mm in diameter were identified in the PLP-MRA group, and fifty were identified in the CTA group (*Table 4*).

The difference between the mean radiographic and intra-operative intramuscular pedicle length was 0.56 cm (0.3–1.1 cm) in the PLP-MRA group (P=0.16) and 1.73 cm (0.5–2.6 cm) in the CTA group (P=0.045). While PLP-MRA measurements of intramuscular pedicle length agreed with intra-operative findings, CTA was found to be significantly different than intra-operative assessments (*Table 5*).

The difference between the mean radiographic and intra-operative distance of the pedicle from the semilunar line was 0.41 cm (0–1 cm) in the PLP-MRA group (P=0.767) and 0.62 cm (0–1.5 cm) in the CTA group (P=0.790) (*Table 6*). Both imaging modalities accurately predicted pedicle distance from the semilunar line.

Discussion

In this study we demonstrated the utility of PLP-MRA to identify radiographic measures that are useful in planning and performing free autologous abdominally-based breast

Table 5 Difference in measured intra-muscular (IM) pedicle length between radiographic imaging study and intra-operative assessment for PLP-MRA and CTA. PLP-MRA closely predicted IM pedicle length while CTA differed significantly from intra-operative assessment, suggesting that CTA may not accurately predict the difficulty of intra-muscular dissection

Variables	Mean (standard deviation), cm	P
PLP-MRA (n=14)		0.16
PLP-MRA IM pedicle length	6.55 (2.42)	
Intra-operative IM pedicle length	6.29 (1.88)	
Imaging *vs.* anatomic difference	0.56 (0.32)	
CTA (n=16)		0.045
CTA IM pedicle length	6.05 (1.65)	
Intra-operative IM pedicle length	5.04 (1.25)	
Imaging *vs.* anatomic difference	1.73 (0.55)	

n, number of hemi-abdomens with perforator flap dissection.

Table 6 Difference in measured distance of pedicle from semi-lunar line between radiographic imaging study and intra-operative assessment for PLP-MRA and CTA. Both PLP-MRA and CTA approximated intra-operative assessment without significant differences

Variables	Mean (standard deviation), cm	P
MRA (n=12)		
PLP-MRA distal position	3.53 (1.28)	0.54
Surgery distal position	3.46 (0.84)	
PLP-MRA proximal position	2.58 (0.70)	0.58
Surgery proximal position	2.58 (1.02)	
CTA (n=12)		
CTA distal position	3.29 (1.03)	0.45
Surgery distal position	3.13 (0.48)	
CTA proximal position	2.21 (0.99)	0.40
Surgery proximal position	2.46 (0.62)	

reconstruction. This MRA protocol can be performed concomitantly with staging breast MRI without the need for ionizing radiation, and it was shown to accurately depict perforator location relative to the umbilicus and from the semilunar line. It also provided additional accuracy when localizing the pedicle's intramuscular course when compared to CTA.

Standard MRA and CTA have been directly compared in a study by Cina and colleagues, which showed that MRA is a reliable method for mapping DIEPs (24). Greenspun and colleagues used an MRI protocol that studied patients in the prone position using a 1.5-T system with gadolinium based contrast, and based on comparison of their results with similar studies of CTA, concluded that the accuracy of MRA was comparable to CTA for determining perforator location (13). They also noted that prone positioning allows for superior perforator imaging with MRA due to reduced motion artifact through reduced respiratory motion.

Another benefit of preoperative imaging is surgical efficiency. Preoperative knowledge of DIEP anatomy has been shown to reduce operative time for DIEP flap harvest (21,22,25-27). The results of our study demonstrate that PLP-MRA provided a significantly more accurate prediction of the intramuscular pedicle length than did CTA. Having this knowledge preoperatively enables the surgeon to predict potential challenges in perforator dissection. Used together with information about the size and number of perforators, a determination about feasibility of DIEP flap harvest can be made with these measurements.

If the pre-operative decision is made for a muscle-sparing design, pedicle distance from the semilunar line can provide guidance on placement of the lateral rectus fascia and muscle incision for flap harvest, and precise locations of perforators will allow the surgeon to know where meticulous dissection is most important (*Table 6*).

Magnetic resonance imaging has become a useful adjunct in evaluation for select cases of breast cancer, including the ability to identify and characterize lesions in a dense breast that cannot be thoroughly evaluated by mammography, localization of lesions seen on only one mammographic projection, improved characterization of benign and malignant masses, better evaluation of tumor extent, evaluation of the contralateral breast, evaluation of axillary adenopathy, and more accurate surveillance in the post-lumpectomy breast (28,29). PLP-MRA is widely available and this imaging technique can be added to the breast MRI imaging protocol to enable that all imaging is carried out in a single session. This has the potential to streamline the care of the breast cancer patient, thereby improving their overall care experience. The concept of seamless delivery of healthcare services has been identified as an effective method to promote optimum patient outcomes and improve patient satisfaction in cancer care (30).

Additionally, there is increasing attention on behalf of physicians and patients on radiation exposure and the increased risk of malignancy associated with the widespread use of CT imaging. This is of particular concern for female patients, who are reported to have a higher risk of cancer development compared to men as a result of CT-associated radiation exposure (31). Moreover, the risk of acute allergic reactions and renal damage due to intravascular contrast administration are lower with gadolinium-based studies such as MRA as compared with iodinated contrast agents used in CTA (24).

As MRI is indicated as part of the imaging workup of a select group of high-risk breast cancer patients, the use of PLP-MRA for both breast imaging and planning of breast reconstruction in these patients would obviate the need for CTA thereby eliminating the risk of future cancer development secondary to radiation exposure, decreasing the chance of allergic reaction and renal damage due to IV contrast, and eliminating treatment delays associated with multiple imaging procedures. Patients who are candidates for free autologous abdominally-based breast reconstruction that do not require MRI as part of their breast cancer workup would also benefit from PLP-MRA solely for preoperative planning, as they would avoid exposure to ionizing radiation from CT and its associated risks. The images from a PLP-MRA are similar to those generated by CT, and the vascular anatomy of the abdominal wall can be easily interpreted by non-radiologist physicians with experience interpreting CT images, making this modality a convenient alternative to CT for the plastic surgeon planning a free tissue transfer.

Conclusions

This study demonstrates that PLP-MRA offers superior accuracy in predicting intramuscular pedicle length compared to CTA, while maintaining accuracy in determining perforator location and pedicle position to assist with flap design. This MRA protocol can be performed in tandem with breast staging MRI, thereby subjecting patients to fewer imaging studies, avoiding treatment delays, decreasing operating time, and preventing exposure to ionizing radiation.

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Footnote

Conflicts of Interest: All authors have completed the ICMJE uniform disclosure form (available at http://dx.doi.org/10.21037/abs.2018.06.02). Podium presentation at the American Society for Reconstructive Microsurgery, Las Vegas, NV, USA, January 2012; Poster Presentation at the 57th Annual Plastic Surgery Research Council, Ann Arbor, MI, USA, May 2012. The authors have no other conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). The study was approved by the Institutional Review Board at Virginia Commonwealth University (No. #13438) and written informed consent was obtained from all patients.

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