Radiofrequency catheter ablation is recommended for patients with sustained ventricular tachycardia (VT) or recurrent implanted cardioverter defibrillator shocks despite medical therapy. However, when compared with patients with postinfarction VT undergoing ablation, patients with nonischemic cardiomyopathy (NICMP) have higher VT recurrence rates, ranging from 47% to 67% in long-term follow-up. This is largely because scar in patients with NICMP is more often located in the midmyocardium or epicardium, and the VT circuit is, therefore, difficult to reach given the limited depth of standard radiofrequency ablation (1.9–6.7 mm).

Percutaneous subxyphoid pericardial access, pioneered by Sosa et al, has provided another route for mapping and ablating epicardial substrate in patients with NICMP VT. However, many challenges remain. The presence of thick epicardial fibrotic tissue and overlying epicardial fat can limit the depth of radiofrequency ablation, and radiofrequency ablation must be avoided near critical structures, such as the coronary arteries or phrenic nerve. In addition, midmyocardial VT isthmuses may not be effectively treated by radiofrequency ablation from either endocardial or epicardial approaches because VT associated with midseptal scar (present in 12%–45% of patients with NICMP VT) is effectively shielded from radiofrequency energy.

High-intensity ultrasound (HIU) is an energy source that applies ultrasound waves with a dedicated frequency (usually 1–10 MHz) at high amplitude (∼10 megaPascals) to generate localized tissue heating and thermal necrosis. HIU allows delivery of deep lesions with minimal effect on superficial tissue and structures, thus providing an attractive energy source for catheter ablation of NICMP VT. We sought to develop an HIU catheter for epicardial VT ablation and compare lesion characteristics with radiofrequency in swine, in vivo. We hypothesized that HIU would demonstrate significantly deeper and larger lesions with greater epicardial sparing in a dose-dependent manner. Further development of this catheter may lead to a promising alternative to epicardial radiofrequency ablation.
WHAT IS KNOWN

- Ventricular tachycardia in patients with nonischemic cardiomyopathy arises from epicardial, midmyocardial, or deep septal regions, which are often difficult to ablate using radiofrequency energy.
- High-intensity ultrasound is a thermal ablation energy source that penetrates deeper into the myocardium than radiofrequency, while sparing the tissue immediately adjacent to the transducer.

WHAT THE STUDY ADDS

- In an in vivo swine model, epicardial high-intensity ultrasound ablation generates deeper and larger lesions than radiofrequency.
- High-intensity ultrasound ablation spares a greater depth of the epicardial surface.
- High-intensity ultrasound is able to effectively ablate through epicardial fat and coronary arteries.
- Further clinical development of this catheter may aid in the treatment of midmyocardial, epicardial, or deep septal ventricular tachycardias.

lead to greater lesion depth, volume, and epicardial tissue sparing compared with radiofrequency. We also sought to explore the safety of HIU ablation over epicardial coronary arteries.

Methods

Epicardial HIU Catheter Design

The HIU components were assembled on 14-French (Fr) flexible nylon catheter (Frellein-Wade Inc; McMinnville, OR; Figure 1). Separate lumens within the catheter house power feed lines and irrigation tubing. To assure orientation of the ablation beam toward the myocardium, an A-mode imaging crystal was added to the catheter. A-mode is the simplest type of ultrasound, whereby a single transducer scans a line through the heart with the echoes plotted immediately adjacent to the transducer.

A-mode imaging ultrasound transducers were mounted on the distal end of the catheter (Figures 1A and 3A). The catheter rotational orientation under fluoroscopy is located on the left anterior descending and left circumflex coronary arteries at least 1 cm apart, avoiding delivering lesions near the coronary arteries. In 2 additional swine, HIU sonication was applied directly over the left anterior descending and left circumflex coronary arteries at 20 and 30 W, respectively, for 60 s each. Coronary angiography was performed before, during, and after sonication to assess for coronary flow, spasm, and thrombus (Figure 3B).

As a control, 5 swine underwent epicardial radiofrequency ablation using an externally irrigated (30 cc/min) ablation catheter (Thermocool, Biosense-Webster; Diamond Bar, CA) via an Agilis steerable sheath (St. Jude Medical; St. Paul, MN) set to continuous suction to evacuate irrigation fluid from the pericardial space. Radiofrequency ablation was started at 25 W, with upwards titration of power to achieve a >10 Ø impedance drop.

At the end of each study, 10 g of 2,3,5-triphenyl-2H-tetrazolium chloride dissolved in 50 mL normal saline was injected intravenously for staining to enhance lesion visualization. hearts were excised and stained with hematoxylin and eosin and Masson trichrome for histological analysis.

This protocol was approved and monitored by the University of California San Francisco Institutional Animal Care and Use Committee under guidelines set forth by the Association for the Assessment and Accreditation of Laboratory Animal Care.

Statistical Analysis

Lesions were measured in 3 dimensions using ImageJ software (National Institutes of Health; Bethesda, MD), and lesion volume was calculated using the ellipsoid formula for HIU lesions (2/3π×l×w×D x[L×W]/2) and half-ellipsoid formula (2/3π×l×w×D x[L×W]/4) where D...
is the lesion depth (from epicardium to endocardium), $L$, the length (along apical–basal dimension), and $W$, the width (along septal–lateral dimension) for radiofrequency lesions. These equations have previously been used for assessment of radiofrequency\(^7\)–\(^9\) and ultrasound\(^{15}\) lesion volumes, respectively. Data are presented as mean±SD.

After performing a generalized estimating equation regression with clustering on pigs, fitted mean values of lesion characteristics were estimated using standardization, and individual HIU power groups were compared with radiofrequency using Sidak-adjusted $P$ values to account for multiple comparisons. $P$ values were 2-sided, and $P<0.05$ was considered significant.

### Results

## A-Mode Ultrasound

In a pilot, open-chest study, the HIU transducer was visually rotated to aim orthogonal to the epicardium, and optimal A-mode tracings were recorded (Figure 2A). The catheter was then rotated 180° to aim directly away from the epicardium and toward the surrounding mediastinum and lung (Figure 2B). Because lung leads to multiple ultrasound reverberations, the difference in A-mode profile between epicardial myocardium and lung was readily apparent. These A-mode profiles were used to guide catheter rotation during closed-chested, in vivo ablations.

## In Vivo Ablation

Percutaneous subxyphoid pericardial access was obtained with the steerable sheath and HIU catheter in 12 HIU-treated pigs, and with the Agilis sheath and Thermocool catheter in 5 radiofrequency-control pigs without complications. The radiopaque S/Z marker was easily visualized under fluoroscopy (Figure 3A) and used to guide catheter rotation, which was further refined by rotation to the optimal A-mode profile (Figure 2A). HIU lesions were applied at 15 W ($n=12$), 20 W ($n=17$), and 30 W ($n=20$) to areas of normal myocardium. Radiofrequency lesions ($n=22$) were delivered with a power of 28.3±6.7 W, starting impedance of 138.3±34.1 Ω, and nadir impedance of 118.4±29.4 Ω, resulting in a mean impedance drop of 19.8±9.8 Ω (14% drop). Lesion depth, epicardial sparing, and volume at all 3 HIU powers and radiofrequency are shown in Figure 4, with characteristic lesions shown in Figure 5.

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**Figure 2.** A-mode ultrasound displaying intensity of acoustic reflections (y axis) over depth (x axis). **A**, Catheter pointed toward epicardium shows thin, mildly echogenic myocardial reflection (arrow) followed by anechoic blood (bracket). **B**, Catheter pointing away from heart shows multiple, highly echogenic reflections of lung tissue.

**Figure 3.** Fluoroscopy of in vivo high-intensity ultrasound (HIU) ablation over basal anterior left ventricle (LV; A), and coronary angiography performed during ablation over left circumflex (LCX) coronary artery (B). **A**, Radiopaque “S” (white arrow) orients ablation away from image intensifier and toward LV anterior wall. **B**, Coronary angiography during HIU ablation directly over LCX demonstrates normal flow without spasm or thrombus.
Depth and volume of HIU lesions demonstrated a direct dose–response relationship with power (Figure 4A and 4C, \(P<0.0001\) for heterogeneity). HIU lesion depth at all powers and HIU lesion volume at 20 and 30 W (\(P<0.0005\) for all comparisons) were significantly greater than radiofrequency, with 30 W demonstrating deepest and largest lesions (12.0±4.2 mm HIU versus 4.7±4.0 mm radiofrequency; 225.0±102.9 mm\(^3\) HIU versus 57.0±108.8 mm\(^3\) radiofrequency). HIU epicardial sparing demonstrated an inverse dose–response relationship with power (Figure 4B, \(P<0.0001\)), was greater than radiofrequency at each HIU power level (\(P<0.0001\) for each comparison), and maximal at 15 W (4.2±1.6 mm versus 0.1±0.2 mm by radiofrequency).

Lesions Over Coronary Arteries
Angiography performed during and after delivery of HIU lesions over the coronary arteries demonstrated thrombolysis in myocardial infarction grade III flow, with no coronary spasm (Figure 3B). At the end of each procedure, the left coronary system remained patent.

Gross pathology, and hematoxylin and eosin–stained and Masson trichrome-stained sections of lesions made over coronary arteries demonstrated no thrombosis or damage to media or intima (Figure 6). Some lesions delivered over coronary arteries (69%) demonstrated disruption of epicardial fat, suggesting acoustic energy absorption by fat. In a subset of these (44%), disruption was noted to also involve the vessel adventitia (Figure 6B and 6C). The thickness of epicardial fat overlying these lesions was 3.6±1.6 mm. In all sections, a lesion characterized by myocardial disruption with contraction band necrosis was noted deep to the coronary arteries (Figure 6B), verifying effective HIU energy delivery through the epicardial fat and coronary arteries. Histological findings are detailed in Table.

Discussion
We have developed a 14-Fr, internally irrigated HIU ablation catheter, and demonstrated its capacity to make lesions that are deeper, larger, and associated with much greater epicardial sparing than radiofrequency energy. Overall, 20-W HIU demonstrated the optimal balance of depth (11.6±3.8 mm) and epicardial sparing (3.2±1.7 mm). HIU was also able to create deep lesions through epicardial fat and coronary arteries without acute coronary injury. These characteristics make HIU an attractive energy source for VT ablation in patients with NICMP, who are likely to have epicardial or midmyocardial VT isthmuses, particularly when scar is located beneath epicardial fat or coronary arteries.\(^5,6,16\) HIU may also be useful in patients with ischemic CMP who have experienced VT recurrence despite ablation with radiofrequency. A-mode guidance allows directed targeting of cardiac tissue away from the lungs and phrenic nerve, the distal irrigated balloon facilitates...
HIU has previously been investigated for catheter ablation of atrial fibrillation, both from a surgical epicardial approach and using a balloon-based endocardial platform. However, HIU’s depth of ablation led to unacceptably high rates of atrioesophageal fistulas from the endocardial approach, leading to eventual abandonment of this technology for atrial fibrillation ablation. One previous study has assessed the use of HIU ablation in the ventricle, creating epicardial lesions in a swine model, although the lesions were created in an open-chest model and not compared with radiofrequency ablation. Our study demonstrates potential clinical benefits of HIU VT ablation by performing catheter-based, closed-chested ablation via percutaneous subxyphoid pericardial access similar to clinical practice. It should be noted that irrigated radiofrequency ablation in our study was performed with a commonly used, commercially available catheter, and at power levels and impedance drops typical of aggressive clinical ablation. Radiofrequency lesion sizes in our study were comparable with those seen in other in vivo studies.

The main limitation of our study is that in vivo lesions were assessed acutely, and swine were not survived to assess lesion development over time, primarily because of cost limitations. Before development for clinical use, HIU lesions, particularly over coronary arteries, should be studied in survival studies to assess chronic lesion sizes, and delayed effects on coronary arteries. The aforementioned open-chested swine HIU ablation study assessed chronic effects of ablation over coronary arteries after 2 to 8 weeks survival, and found that, although there was some progression of coronary pathology over time, overall 64% of lesions were free of significant injury. Furthermore, HIU ablation characteristics in areas of myocardial scar should be investigated because acoustic characteristics of healthy and scarred myocardium may differ.

Future generations of this HIU catheter will decrease catheter diameter from current 14 Fr and incorporate steerability (currently positioned using steerable sheath) to allow

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**Table. Histological Analysis of Lesions Over Coronary Arteries**

<table>
<thead>
<tr>
<th></th>
<th>Fat Disruption (%)</th>
<th>Adventitial Disruption (%)</th>
<th>Intimal Disruption</th>
<th>Epicardial Fat Thickness (mm, mean±SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAD (n=12 lesions)</td>
<td>8 (67)</td>
<td>6 (50)</td>
<td>0 (0)</td>
<td>3.9±1.7</td>
</tr>
<tr>
<td>LCX (n=4 lesions)</td>
<td>3 (75)</td>
<td>1 (25)</td>
<td>0 (0)</td>
<td>3.3±1.3</td>
</tr>
<tr>
<td>Total (n=16 lesions)</td>
<td>11 (69)</td>
<td>7 (44)</td>
<td>0 (0)</td>
<td>3.6±1.6</td>
</tr>
</tbody>
</table>

LAD indicates left anterior descending coronary artery; and LCX, left circumflex coronary artery.
assessment of endocardial ablation. Geometric focusing of the HIU beam may further improve epicardial and coronary sparing. On the basis of HIU lesion depth demonstrated, endocardial HIU may also allow ablation of epicardial VT from an endocardial approach, thus obviating the need for higher risk pericardial access. If endocardial lesions are similar to the epicardial lesions demonstrated here, HIU ablation may also allow ablation of deep septal VTs, which are currently challenging to ablate using radiofrequency from either side of the interventricular septum.20,21

In conclusion, we have developed an internally irrigated, side-facing, epicardial HIU catheter, capable of making large, deep lesions with sparing of epicardial tissue. Dose ranging studies showed that 20-W lesions had the best balance of depth of penetration and epicardial sparing. Lesions were effective even through epicardial fat, and direct application over coronary arteries led to effective lesions without intimal coronary injury. Further development of this catheter may lead to a viable alternative to radiofrequency ablation.

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Disclosures
None.

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Epicardial Catheter Ablation Using High-Intensity Ultrasound: Validation in a Swine Model
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