Use of a Novel Endoscopic Catheter for Direct Visualization and Ablation in an Ovine Model of Chronic Myocardial Infarction

Running title: Betensky et al.; Direct Visualization Catheter

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Abstract:

Background - Defining the arrhythmogenic substrate is essential for successful ablation of scar-related ventricular tachycardia (VT). The visual characteristics of endocardial ischemic scar have not been described in vivo. The goal of this study was to 1) quantify the visual characteristics of normal tissue, scar border zone and dense scar in vivo using a novel endoscopic catheter that allows direct endocardial visualization and 2) correlate visual attributes of myocardial scar with bipolar voltage.

Methods and Results - Percutaneous transient balloon occlusion (150mins) of the mid-LAD coronary artery was performed in an ovine model. Animals were survived for 41.5±0.7 days. Detailed bipolar voltage maps of the left ventricle were acquired using NavX. Video snapshots of the endocardium were acquired at sites distributed throughout the left ventricle. Visual tissue characteristics of normal (>1.5mV), border (0.5-1.5mV) and dense scar (<0.5mV) were quantified using image processing. Radiofrequency (RF) lesions (10-20W, 30secs) were delivered under direct visualization. Mean white-threshold pixel area was lowest in normal tissue (189,969 ± 41,478pixels²), intermediate in scar border zone (255,979 ± 36,016pixels²) and highest in dense scar (324,452 ± 30,152pixels², p<0.0001 for all pairwise comparisons). Tissue "whiteness", characteristic of scar, was inversely correlated with bipolar voltage (p<0.0001). During RF lesions, there was a significant increase in white-thresholded pixel area of the visual field after ablation (average increase 85,381 ± 52,618 pixels²; P<0.001).

Conclusions - Visual characteristics of chronic infarct scar in vivo using a novel endoscopic catheter correlate with bipolar electrogram voltage. Irrigated RF lesions in normal endocardial tissue and post-infarction zone can be visualized and quantified using image processing. This technology shows promise for visually based delivery of RF lesions for the treatment of scar-based VT.

Key words: ablation; animal model; catheter ablation; myocardial infarction; ventricular tachycardia

Introduction
Mapping of poorly tolerated ventricular tachycardia (VT) combines reconstruction of cardiac anatomy and scar using electroanatomic voltage mapping (EAM) and pacemapping to locate VT exit sites.1-2 Ablative therapy uses an anatomic approach of lesion delivery in a linear fashion through the infarct border zone and may include ablation of late and fractionated potentials presumed to represent zones of slow conduction capable of sustaining VT.3-6 Despite the advent of these “substrate modification” techniques that allow ablation of VT that is not tolerated hemodynamically, the long-term result of VT ablation remains suboptimal. In the recent randomized VTACH study, the 2-year success rate after ablation of VT in patients with ischemic cardiomyopathy was 47%.7 In addition to an evolving substrate, some of the limitations of substrate-based ablation include indirect localization of myocardial scar using voltage mapping, poor catheter-myocardial contact during radiofrequency (RF) delivery, difficulty delivering contiguous lesions and challenges in achieving adequate lesion depth in dense scar.

Given the largely anatomic approach to ablation of poorly tolerated VT in many centers, direct visualization of the myocardium may offer advantages to the indirect visualization offered by current EAM systems. These advantages include direct visualization of infarct heterogeneity and location, catheter stability, lesion development and lesion contiguity. A novel endoscopic catheter (IRIS Cardiac Ablation Catheter, Voyage Medical Inc., Redwood City, CA) allows direct visualization of endocardial tissue during mapping and delivery of irrigated radiofrequency ablation. Using this catheter in an ovine model of myocardial infarction, we hypothesized that 1) we could quantify and differentiate the visual characteristics of normal endocardium, infarct border zone and dense scar; 2) scar characteristics defined by visual assessment would correlate with bipolar voltage recorded from the catheter tip, and 3) we could visualize and quantify ablative lesions delivered to normal tissue, infarct border zone and scar.
We also assessed the size of ablative lesions delivered with this novel catheter at different power settings.

**Methods**

*Study design*

The study was performed in ovine following creation of a myocardial infarction using transient balloon occlusion of the left anterior descending coronary artery. This study was approved by the University of Pennsylvania Institutional Animal Care and Use Committee and was performed within ULAR institutional guidelines.

*Catheter Description*

The IRIS catheter is designed for visualization of anatomical structures within the heart, cardiac mapping, and delivery of RF energy to myocardial tissue for the treatment of cardiac arrhythmias. The catheter is an open irrigation, direct visualization catheter consisting of a steerable 12.5 Fr catheter with a distal self-expanding flexible hood (6.8mm), open aperture in the center of the hood face (3mm), and an integrated high-resolution flexible fiberscope and illumination bundle (Figure 1). The catheter has 4 electrodes (2 mm inter-electrode bipolar spacing) on the hood surface and an additional 8 electrodes on the outside of the hood to allow for localization of the catheter using an impedance-based mapping system. With the hood in contact with the endocardium, a constant saline flush (5-10cc/min) is used to keep the hood free of blood and allows for direct visualization of the endocardial surface. The video images are displayed on a monitor in the lab and recorded by an external system for digital archive and review. Brightness settings and camera focus were calibrated at the start of each experiment to optimize tissue clarity. The catheter handle contains a steering device that combines a primary...
unidirectional curve of up to 180 degrees with a 4-way steering mechanism that allows for fine movements of the catheter tip in 3 dimensions.

The hood contains a 2.7 mm electrode; when radiofrequency energy is delivered to the electrode, the saline serves as a medium to conduct current to the tissue, i.e. a “virtual” RF electrode. This allows irrigated ablation from the 6.8mm diameter catheter hood without direct electrode contact with the endocardium, with the effective “electrode” area being the 3mm hood aperture. During ablation, saline irrigation is maintained at up to 25cc/minute using an irrigation pump.

*Myocardial Infarction Protocol*

All animals were placed under general anesthesia. After induction with ketamine and buprenorphine, all animals were intubated and placed under general anesthesia with inhaled isoflurane 1-2% and mechanically ventilated. Vascular access was obtained through the femoral artery and vein using standard hemostatic sheaths. Temperature was maintained at > 37 degrees Celsius using a warming blanket and warmed saline. An intracardiac echo catheter (AcuNav, Siemens Medical, Mountain View, CA) was used to visualize the left ventricle during infarct creation. A quadripolar pacing catheter was advanced to the right ventricular apex in case pacing was needed. Each sheep received lidocaine (50mg IV bolus) followed by a continuous infusion at 1mg/minute. The left main coronary artery was engaged with a hockey-stick guide sheath and a coronary angiogram was performed using iopamidol contrast media. An appropriately sized angioplasty balloon (2.5-3mm diameter x 10-20mm length) was advanced just distal to the second diagonal branch and inflated for 150 minutes. The mean arterial pressure was maintained >70mmHg throughout the infarction using an IV neosynephrine drip titrated to effect. At the end of the procedure, all hemostatic sheaths were removed and the sheep was extubated and
Endocardial Mapping

After 4-6 weeks survival, sheep were taken back to the catheterization lab and intubated under general anesthesia, with intravenous and arterial access as described above. A coronary sinus catheter was placed at the start of each experiment and used a NavX reference for geometry reconstruction (Figure 2). An intracardiac echocardiography catheter was used in all cases for guiding transseptal access and infarct visualization (Figure 2). A heparin bolus of 10,000 units was administered and repeat boluses were given throughout the procedure to maintain an ACT > 250 seconds. Transseptal puncture was performed with a standard 8 Fr sheath and then changed over a wire to a custom 14 Fr fixed, 110 degree curve sheath (Voyage Medical Inc., Redwood City, CA) in order to access the left ventricle. After initial mapping was performed, the intracardiac echocardiography catheter was exchanged for a right ventricular quadripolar pacing catheter positioned at the RV apex, in order to perform programmed electrical stimulation.

The eight electrodes located on the hood exterior allowed catheter tip localization with the NavX mapping system (St Jude Medical, Minnetonka, MN), and the 4 electrodes on the IRIS hood were used to simultaneously record bipolar voltage. A left ventricular geometry was created and then a detailed bipolar voltage map was superimposed on the LV geometry (Figure 2). Dense scar (<0.5mV), border zone (0.5-1.5mV) and healthy tissue (>1.5mV) were defined using previously described voltage cutoffs.4,8 Individual recording sites were distributed throughout the LV at points of stable apposition of the catheter hood with the myocardium. At each site a video image was captured and the location was tagged and electrograms recorded on the NavX system for offline analysis. Mean bipolar electrogram voltage was calculated by averaging the 4 bipolar electrode pairs (1,2; 2,3; 3,4; 4,1) on the catheter tip and was correlated recovered.
with the simultaneous visual snapshot of the myocardium at each site (Figure 3).

**Image Processing**

Video snapshots of each region were acquired off-line using Corel VisualStudio 12. Bitmap images were imported into the Fiji Package for ImageJ, an open source Java-based image processing application developed by the National Institutes of Health. Individual color images were contrast enhanced and color thresholded to best approximate red-white tissue borders. Thresholding parameters were pre-set to "default" mode with an “HSB” color space. Saturation and brightness were initially fixed at 0-255. Hue was the first parameter assessed by setting the color range to 0-15. The upper limit was then decreased in a stepwise fashion until "red" regions appeared to breakthrough between the "black" regions and the "white" regions. Once this was established, the saturation parameter was adjusted to avoid counting the 4 white electrodes. The image was then converted to 8-bit format for particle analysis. Images were analyzed in a random chronologic order. Pixel measurement settings were standardized for ensuring consistent particle analysis measurements. All images with blood in view were excluded, as to not falsely affect tissue whiteness.

**Radiofrequency Lesion Delivery**

Following completion of geometric and voltage data acquisition, a series of radiofrequency lesions were delivered to regions of healthy, border and dense scar tissue for 30 seconds each at powers of 10 Watts, 15 Watts and 20 Watts. During RF energy delivery irrigation was maintained at 25cc/minute. Constant power delivery was maintained for each lesion; no attempt was made to titrate power delivery based on visual findings in order to determine histopathologic correlation to the different power settings. Local bipolar electrograms were recorded before and immediately after RF delivery. The time to tissue blanching (TTB), defined as the time until the
field of view through the central 6mm aperture was completely white, was recorded by 2 independent observers. It was hypothesized that this measure, reflective of scar formation during ablation, would differ among normal myocardium, border zone and dense scar.10-11

Gross Anatomy and Histopathology

At the conclusion of the mapping and lesion study, while under a deep plane of anesthesia, sheep were euthanized and the hearts were explanted. The hearts were then incised posteriorly to provide a postero-anterior view of the endocardial surface. Scar distribution and RF lesions were visually inspected and then marked using colored sutures to denote power delivery for each lesion. The hearts were then immersed in 10% buffered formalin. Following fixation, the RF lesions were identified, grossly trimmed and the width and depth of each lesion was measured with a hand caliper. Trimmed sections were embedded in paraffin, cut 4mm thick and stained with Masson’s trichrome (Histo Tec Laboratory, Hayward, CA). Histology slides were evaluated with a light microscope and histopathologic findings were recorded.

Statistical analysis

To accommodate the repeated measurements on each animal, linear mixed models were used to compare tissue types and assess the association of tissue whiteness and voltage. Pairwise comparisons between groups were corrected for multiple testing using the Sidak method. The Kenward-Roger approximation was used to account for small sample sizes and sensitivity to the assumed variance-covariance structure was checked using robust standard errors. Voltage was log transformed to linearize the relationship to whiteness. The significance of the overall tissue whiteness change from before to after ablation as well as lesion width and depth were also assessed using mixed model analyses as described above. The analysis included terms for tissue type, power and their interaction. Analyses were performed using SPSSv16.0 statistical software
(SPSS, Chicago, Illinois) and SASv9.2 (SAS Institute, Cary, North Carolina).

Results

Eight male Hunter-Dorset sheep were included in this study. Animals were survived for a mean of 41.5±0.7 days after infarct creation. Detailed bipolar endocardial voltage maps were acquired in each animal. In the 8 animals, visual images and mean bipolar voltage were examined and compared at 148 sites: normal tissue (n=75), border zone (n=49) and dense scar (n=24). At an additional 60 sites (normal=32, border=20, dense scar=8) bipolar voltage and image analysis were performed before and after RF ablation.

Visual Characterization of Tissue Types

Visually, there were clear differences among the tissue types under direct visualization, with healthy myocardium appearing pink/red, dense infarct white, and infarct border zone with red/white intermingled fibers (Figure 3). These qualitative findings were quantified by counting the “whiteness” of each visual field after white-thresholding. The mean white-thresholded pixel area (range 97,569 - 398,002 pixels²) was significantly different among healthy endocardium, border zone and dense scar (Figure 4A, p<0.0001 for all pairwise comparisons). Mean peak-to-peak bipolar voltage (range 0.16-19.64mV) was inversely correlated with mean white-thresholded pixel area. With each doubling of voltage, white-thresholded pixel area was estimated to decrease by about 62,100 pixels (p<0.001) (Figure 4B).

Visual Characterization of Radiofrequency Lesions

Delivery of RF lesions (n=60) were visualized in real-time using the IRIS catheter (Figure 5). RF lesions were marked by an initial quiescent period, followed by marked, rapid tissue whitening starting at the center of the visual field and radiating outward. Small micro-bubbles could be seen developing during higher power energy delivery. At the highest power (20W), a nonaudible
steam “pop” was observed only once during RF delivery. Microbubbles were visualized and increased in volume prior to the steam pop occurring. Endocardial coagulum or thrombi were not observed during ablation. After each lesion was delivered, the catheter could be navigated around the lesion borders, which were clearly demarcated in vivo. Each lesion was delivered individually, separate from the others to allow for later histological analysis of lesion size. There was a significant increase in white-thresholded pixel area of the visual field both within each tissue type (P<0.001 for each type) and overall (average increase 85,381 ± 52,618 pixels$^2$; P<0.001) after ablation. Visually, even lesions appearing in dense scar were readily apparent.

Despite subjective appearance of more robust visual field whitening during the highest power (20W lesions), the TTB was not significantly correlated with tissue type when all lesions were grouped together (dense scar 16.3±10.4 vs. border zone 12.6±7.0 vs. normal 14.7±4.8 secs, p=0.339).

**Histopathology of the left ventricle and RF lesions**

Sections of the ventricle had large regions of chronic infarct scar tissue, as well as regions that had acute coagulative necrosis of the myocardial fibers. The scar tissue (infarct) as represented by regions of fibrous connective tissues mixed with a collagenous matrix. Zones of persisting normal myocardial fibers were interspersed within the chronic scar. The acute ablation foci were well demarcated, consisting of swollen and dark myocardial fibers with loss of cellular detail along with interstitial edema and congestion/hemorrhage (Figure 6). Ablation lesions were either individually localized separated by zones of healthy myocardial tissue or adjacent to and within infarct scars. In the latter case, RF application targeted the surviving myocardial fibers still persisting in previously infarcted tissue. These isolated sheets of myofibers sustained complete thermal necrosis (Figure 6).
Of the 62 lesions delivered, 45 lesions were identified during histopathologic examination. Sizeable lesions were achieved across all tissue types (width 6.5±2.0mm, range 2.0-16.0mm; depth 5.2±1.9mm, range 2-10mm). Lesion width (10W vs 15W vs. 20W adjusted mean ± SEM; 5.2±0.8mm vs. 6.1±0.6mm vs. 8.1±0.6; p=0.01) and depth (2.9±0.7 vs.5.4±0.6mm vs. 5.8±0.6mm, p=0.0003) increased with increasing power (Figure 7).

Discussion

We found that a novel endoscopic catheter allows real-time visualization of the left ventricular endocardium during mapping and irrigated radiofrequency ablation. Direct visualization allowed the operator to differentiate among electrogram-defined dense scar, border zone and normal tissue in an ovine model of chronic myocardial infarction. The difference in tissue characteristics among these regions was readily apparent visually, and these visual findings could be quantified using image processing demonstrating a direct inverse correlation between visual field “whiteness” and bipolar electrogram voltage. Direct visualization was also performed during irrigated RF ablation, with qualitative and quantitative whitening of the visual field occurring during ablation. RF lesion visualization was most pronounced in normal tissue, but also readily apparent in dense scar. Microbubble formation was rarely seen at higher powers, and in one case presaged a steam pop.

These findings introduce a new paradigm in catheter ablation. Initially, catheter ablation was guided indirectly by fluoroscopy and electrograms recorded from the electrode tip. The advent of electroanatomic mapping allowed one to construct a virtual geometry, and with computed tomographic or magnetic resonance image registration, an indirect representation of the cardiac chamber anatomy and catheter location. Intracardiac ultrasound provided the first real time feedback of anatomy during ablation, however the anatomic rendering was limited.
by the resolution and field of view of ultrasound.\textsuperscript{16-19} Now, direct visualization of the endocardial surface is feasible during mapping and ablation. This has many important implications. Many arrhythmias are targeted using a combination of electrical and anatomic information, including atrial fibrillation, atrial flutter, papillary muscle VT and VT in ischemic cardiomyopathy. Ablation of VT that is poorly tolerated hemodynamically is performed using a combination of pacemapping and linear ablation through the scar border zone. Some have advocated scar “homogenization”, with ablation of all portions of electrically active scar or late potentials that might harbor future VT circuits. The IRIS endoscopic catheter can be used to rapidly construct a voltage map that identifies the location of scar and border zone. Ablation can then be performed through regions of border zone with direct visual confirmation. In addition, ablation of other areas of presumably viable tissue throughout the scar can be performed empirically.

There may be other advantages to direct visualization during ablation. Visualization ensures catheter contact during ablation, since one cannot visualize the endocardium until contact is achieved and the saline flush clears blood from the field of view. This will likely enhance the depth and consistency of ablative lesions. Furthermore, tissue blanching during radiofrequency delivery actually confirms the tissue has reached an adequate temperature for irreversible thermal necrosis. It has been previously demonstrated that tissue optical properties change as the tissue is heated based on increased light scattering from denatured proteins and changes to mitochondria (what we observe as “blanching”). These visual/optical changes have been found to occur in the 50-60\textdegree C range.\textsuperscript{10-11, 20-21}

Visual feedback during ablation also may prevent complications via early visualization of thrombus and avoidance of steam pops due to downward titration of power when aggressive micro-bubbles appear. Linear, contiguous lesions may also be assured by visually connecting...
individual lesions. Previous lesions can also be revisited quite easily should the catheter be repositioned. Contact with certain challenging anatomic structures, such as the papillary muscle, can be confirmed prior to ablation. Furthermore, ablation through the “virtual” electrode saline irrigant may also have advantages over contact electrodes. Energy delivery is more uniform and efficient, since the RF energy is delivered directly to the myocardium in the field of view. This is in contrast to contact irrigated catheter ablation, where energy delivery may vary significantly depending on catheter orientation due to the variable electrode/myocardial interface and loss of energy to the surrounding blood pool.22 Lastly, the flat 6 mm distal hood surface is also less likely to lead to cardiac perforation; we have never seen a perforation despite aggressive catheter manipulation in this animal model.

Prior work

Two visualization catheters have been reported previously, including CardioFocus Endoscopic Ablation System (CardioFocus Inc., Marlborough, Massachusetts), and the FLEXview system (Boston Scientific Cardiac Surgery, Santa Clara, CA).23 24 CardioFocus uses a small endoscope to allow visualization through a balloon placed in the pulmonary vein ostium. This system is designed specifically for PV isolation and such a balloon cannot be maneuvered around a cavity such as the left ventricle. The FLEXview system is a gastroenterology endoscopy catheter that was adapted for use in epicardial visualization. This catheter did not have the ability for fine mapping, recording of electrical signals, nor ablation. None of these studies addressed scar based models of VT.

Limitations

There are several limitations to the endoscopic catheter system. Visualization requires endocardial contact; no visualization occurs when manipulating the catheter inside the LV.
cavity. We used an electroanatomic mapping system to guide catheter manipulation, localization, and rendering of the voltage map to define the location of endocardial scar. These combined modalities may increase the cost of the procedure, however with additional use it is likely that the endoscopic catheter could be used without a mapping system. A large amount of saline is given throughout these procedures, as a constant infusion is need both during mapping and ablation. This may be reduced in future versions of the catheter.

The absolute value for tissue “whiteness” was determined offline. Further investigation is warranted to determine whether more automated software capable of real-time, online quantification for visual-based mapping is feasible and to establish clinical reference values for different tissue types. Although visual blanching is the hallmark of lesion formation and progressively deeper lesions were achieved at higher powers, a statistically significant correlation between lesion depth and change in tissue whiteness pre/post ablation or time to initial blanch was not observed in this study. Thus, further research is needed to develop visually based criteria that may help to predict lesion depth. Lastly, we recognize that the optical properties of endocardial tissue varies between cardiac chambers and that there may exist species-specific differences in the “whiteness” of ventricular endocardium at baseline, potentially limiting the generalizability of our results to humans with chronic myocardial infarction.

Conclusions
A novel endoscopic catheter is capable of direct endocardial visualization during mapping and ablation in an ovine model of chronic myocardial infarction. Using this catheter, we were able to visualize and quantify differences in tissue characteristics among normal myocardium, border zone, and dense scar. Irrigated RF lesions were visualized during and after ablation in both
normal tissue and dense scar. Integration of direct visualization with current mapping techniques may enable visually guided ablation of heterogeneous scar capable of supporting VT. This technology shows promise for visually based delivery of contiguous RF lesions for the treatment of scar-based VT.

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**Conflict of Interest Disclosures:** Dr. Marchlinski is on the scientific advisory board of Voyage Medical Inc. Dr. Wylie is an employee of Voyage Medical Inc. Dr. Oley is an employee of Voyage Medical Inc. Dr. Robinson is an employee of Voyage Medical Inc. Dr. Gerstenfeld has an investigator initiated research grant from Voyage Medical Inc. and is on the Scientific Advisory Board of Voyage Medical Inc.

**References:**


**Figure Legends:**

**Figure 1.** Voyage IRIS Ablation Catheter. The 12.5 Fr catheter has a flexible 6.8mm hood (magnified view) that allows direct endocardial visualization once blood is flushed from the hood using saline irrigation. Ablation is performed via a 2.7 mm electrode at the base of the hood. Bipolar electrograms can be recorded using electrodes on the face of the hood.

**Figure 2.** Voltage Mapping. Top: NavX voltage map (0.1 – 1.5mV) of left ventricular endocardium after percutaneous anteroseptal myocardial infarction. Purple represents normal
endocardium. Note the heterogeneous anteroseptal scar. Bottom Left: Fluoroscopy image of IRIS catheter in LV abutting the endocardium (red arrow). Bottom Right: Intracardiac echocardiographic image demonstrating catheter articulation and endocardial positioning during ablation in the inferoseptal LV (red arrow). ICE = intracardiac echocardiography; CS = coronary sinus

**Figure 3.** Representative Examples of Direct Endocardial Visualization. Direct endocardial visualization using the IRIS Cardiac Ablation Catheter in three voltage-defined tissue types and corresponding ImageJ-thresholded images and recorded bipolar electrograms. The peak-to-peak amplitude of the electrograms and white-thresholded pixel count of each visual field is shown.

**Figure 4.** Correlation of Tissue-Whiteness with Electrogram Bipolar Voltage. A. Mean white-thresholded pixel area was significantly different between three bipolar electrogram-defined tissue types, potentially enabling independent identification of tissue type by visual criteria alone. B. Mean local peak-to-peak bipolar voltage was inversely correlated with visual tissue “whiteness” (p<0.0001).

**Figure 5.** Sequential Real-Time Endocardial Radiofrequency Lesion Development. Examples of stereotypical appearance of lesions created over time in the infarct border zone at 10W, 15W and 20W power delivery.

**Figure 6.** Lesion pathology. A: Gross image of lesions made with the IRIS catheter in a healthy heart. The lesion was delivered at 10W for 30 seconds and measured 5.7mm in width x 3mm
depth. B: Lesion histopathology: photomicrograph illustrates an ellipsoidal area of acute RF ablation below the endocardial surface (E) leading to tissue alteration including cellular coagulation (A) with interstitial swelling and edema. This is followed by a paler band (*) of ablated tissue ablation separating it from a darker (^) leading edge of the acute ablation (compacted / congestion) beyond which is a lighter zone of tissue contraction leading to healthy, normal myocardium. C: Gross image of lesions made in an anteroseptal area of myocardial infarction. These lesions were delivered at 10w for 30 seconds and measures 5.7mm in width and 3mm depth. D: Histopathology: ablation lesion (A) and scar border (*) leading to infarct zone (I). Chronic scar appears pale (light blue). Normal cardiomyocytes which have undergone acute coagulation necrosis are characterized by dark blue homogeneous bands with a lack of cellular detail and swollen cytoplasm.

**Figure 7.** Lesion depth as a function of power. Mean lesion depth increased with progressively higher delivered power (p<0.001).
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<th>Tissue Type</th>
<th>Endocardial Surface</th>
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<th>Bipolar Electrogram</th>
<th>Bipolar Voltage (mV)</th>
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SUPPLEMENTAL MATERIAL
**Movie Legend**

**Movie 1:** Left panel: Electroanatomic voltage map of the swine left ventricle showing catheter position on the mid-septum. Right panel: Video of the scar border zone during radiofrequency ablation. Note the heterogeneous appearance of the scar tissue at baseline and the whitening that occurs during ablation.