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Thermal Chondroplasty with Radiofrequency Energy

An In Vitro Comparison of Bipolar and Monopolar Radiofrequency Devices

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ABSTRACT

The purpose of this study was to examine the in vitro effects of three radiofrequency energy devices (two bipolar devices and one monopolar device) for the performance of thermal chondroplasty. Thirty-two fresh bovine femoral osteochondral sections (approximately 3 × 4 × 5 cm) from eight cows were divided into four groups (three treatment patterns and one sham-operated group with eight specimens per group). The three treatment patterns consisted of 1) radiofrequency energy delivered by a mechanical jig at 1 mm/sec in a contact mode (50 g of pressure), 2) radiofrequency energy delivered by a mechanical jig at 1 mm/sec in a noncontact mode (1 mm between probe tip and articular cartilage surface), and 3) radiofrequency energy smoothing of abraded cartilage during arthroscopic visualization. Thermal smoothing of the abraded cartilage surface was accomplished with all three devices. Significant chondrocyte death, as determined by confocal laser microscopy and cell viability staining, was observed with each device. The bipolar radiofrequency systems penetrated 78% to 92% deeper than the monopolar system. The bipolar systems penetrated to the level of the subchondral bone in all osteochondral sections during arthroscopically guided paintbrush pattern treatment. Radiofrequency energy should not be used for thermal chondroplasty until further work can establish consistent methods for limiting the depth of chondrocyte death while still achieving a smooth articular surface.

Articular cartilage is a specialized tissue that plays a crucial role in the absorption and distribution of forces encountered during daily activities. Cartilage depends on an intact matrix for its biochemical and mechanical characteristics, and loss of cartilage structure and function leads to chondromalacia and osteoarthritis.[3,4] The mechanisms underlying the pathophysiology of these diseases involve progressive cartilage erosion and reactive synovitis secondary to cartilaginous debris and cytokine production.[2–4,19,20]

When presented with patients suffering from joint pain, the orthopaedic surgeon has few options for the treatment of swollen fibrillated cartilage and partial-thickness cartilage defects. Mechanical debridement (chondral shaving) is a common approach in the management of partial-thickness cartilage defects, but it results in fine surface fibrillation of the remaining debrided cartilage after the procedure is completed. The goal of chondral shaving is to selectively debride the affected cartilage regions without deleteriously affecting the surrounding healthy cartilage.

Radiofrequency energy is gaining widespread use in the field of sports medicine surgery for the thermal modification of soft tissue structures within the joint (Refs. 7, 8, 24; J. R. Andrews, unpublished data, 1999; D. D'Alessandro, unpublished data, 1999; G. S. Fanton, unpublished data, 1999; and R. F. Warren, unpublished data, 1999). Monopolar and bipolar radiofrequency energy have become frequently used arthroscopic techniques for the thermal mod-

ification of intraarticular soft tissue structures. The use of radiofrequency energy for thermal chondroplasty also has gained tremendous popularity over the past 3 years for several reasons. Radiofrequency energy is an inexpensive surgical tool that is relatively safe for the patient, surgeon, and operative personnel, and it may be delivered arthroscopically with a wide variety of probes that offer extended flexibility to the surgeon. Monopolar radiofrequency energy also has the added advantage of providing temperature-controlled application, thus potentially widening the margin of safety when treating intraarticular structures. The effects of radiofrequency energy on the periarticular soft tissue structures have been investigated,[9–12,17,21] but limited investigation of its use on articular cartilage is present in the peer-reviewed literature.[15,25]

Thermal modification might allow alteration of the mechanical or structural properties of the superficial portion of articular cartilage and slow or stop the degenerative changes seen in osteoarthritic or chondromalacic cartilage.[25] It is hypothesized by surgeons who use radiofrequency energy that the alteration of the cartilage surface may also reduce the release of collagen and proteoglycan epitopes into the synovial fluid and reduce the cycle of cartilage degradation, synovial inflammation, and further articular degeneration. Based on the sales of radiofrequency energy systems and their application, it appears that many orthopaedic surgeons in the field of sports medicine are actively using radiofrequency energy to modify the articular surfaces of damaged cartilage during the arthroscopic examination of abnormal joints. While anecdotal reports through discussions with surgeons and second-look arthroscopy might indicate that patients are clinically improved after the radiofrequency treatment of the articular cartilage surface, a long-term objective assessment of cartilage modification by radiofrequency energy has not been performed. Three in vivo studies using animal models to investigate the effects of radiofrequency energy on articular cartilage report conflicting outcomes.[15,18,25] The purpose of this in vitro study was to assess the effects of monopolar and bipolar radiofrequency energy systems on articular cartilage at the manufacturer's recommended settings. We hypothesized that thermal smoothing of the articular cartilage surface can be achieved with these devices, but that unacceptable thermal injury to the chondrocytes would occur with the available radiofrequency energy systems at the manufacturers' recommended settings.

MATERIALS AND METHODS

Thirty-two fresh bovine osteochondral sections (approximately $3 \times 4 \times 5$ cm) from the distal femoral condyles of eight cows were divided into four groups (eight specimens per group). Cartilage thickness of the distal femoral condyle ranged from 2 to 3 mm and was considered consistent with the thickness of the human femoral condyle.[1] All treatments were performed with the specimen in physiologic saline (0.15M) at 22°C. In each treatment group, eight different osteochondral sections with macroscopi-

cally normal cartilage from eight separate cows were treated using one of three radiofrequency devices: TAC-C probe, ElectroThermal System ORA-50 (Oratec Interventions Inc., Menlo Park, California); VAPR Flexible Side Effect Electrode (3.5-mm), Mitek VAPR System (Mitek Products, Inc., a division of Ethicon Inc., Westwood, Massachusetts); 3.0 mm $\times$ 90° ArthroWand #A 1330, Arthroscopic Electrosurgery System (ArthroCare Corporation, Sunnyvale, California). The remaining eight sections from eight separate cows served as sham-operated controls. Radiofrequency energy treatment of each section was assigned in random fashion.

Radiofrequency effects on cartilage were assessed after each of three different treatment applications. One radiofrequency probe pass was performed with a motorized jig that applied 50 g of weight through the probe tip at a velocity of 1 mm/sec to simulate a single, controlled pass across the cartilage with contact (single-pass contact mode). Fifty grams of pressure had previously been determined in pilot studies to approximate the pressure applied when treating cartilage with the monopolar devices. The second treatment was performed with a motorized jig that maintained the probe tip 1 mm from the cartilage surface at a velocity of 1 mm/sec (single-pass noncontact mode). The probes were maintained at 1 mm from the articular cartilage surface with a standoff on the probe that maintained the desired distance. One millimeter was chosen as an approximate or average distance used by orthopaedic surgeons clinically. The third treatment was designed to mimic the clinical application of radiofrequency energy for thermal chondroplasty of abraded articular cartilage. The cartilage surface (10×10 mm) was abraded using a custom-made tool that created 0.5-mm clefts and fibrillation within the cartilage surface. This area was treated in a clinical manner (paintbrush treatment pattern) using an arthroscopic technique until smoothing of the surface was observed. Each section was treated using the manufacturer's recommended settings (Oratec, 55°C/25 W; Mitek, V2:40 W; ArthroCare, controller setting of 2). Treatment of the abraded cartilage surface was terminated when the surface was considered smooth as determined by two experienced surgeons, and treatment time was recorded. The two bipolar systems (ArthroCare and Mitek) were used in a noncontact mode and the monopolar system (Oratec) was used in a contact mode, as recommended by the manufacturers.

After treatment, osteochondral blocks were cut with a band saw, under phosphate-buffered saline solution irrigation to prevent frictional heat, into small osteochondral blocks, including the treated area, with 0.5 cm of its associated subchondral bone. A low-speed saw (Buehler, Isomet 2000, Lake Bluff, Illionios) was used to cut the osteochondral block into slices of 1.0 or 2.0 mm thickness. The 1.0-mm thick slices were analyzed for chondrocyte viability by confocal laser microscopy on the same day of the treatment. The 2.0-mm thick slices were processed for scanning electron microscopy.

The 1.0-mm thick cartilage slices were stained by incubation in a 1.0-ml phosphate-buffered saline solution containing 0.4 μl calcein (acetoxymethylester)/13 μl ethidium

homodimer (Molecular Probes, Eugene, Oregon) for 30 minutes at room temperature. The method of determining the location of surviving cells was based on the knowledge that viable and nonviable cells differ in their ability to exclude fluorescent dyes.[22] The cell membranes of dead, damaged, or dying cells are penetrated by ethidium homodimer to stain their nuclei red. Living cells with intact plasma membranes and active cytoplasm metabolize calcein (acetoxymethylester) and show green fluorescence. The method of analysis was a 1.0-mm thick cartilage slice that was placed on a glass slide and moistened by several drops of phosphate-buffered saline. A confocal laser microscope (MRC-1024, Bio-Rad, Hemel Hempsted/Cambridge, England) equipped with a krypton/argon laser and the necessary filter systems (fluorecein, 522DF32, and rhodamine, 585EFLP) was employed using the triple-labeling technique. In this technique, the signals emitted from double-stained specimens can be distinguished because of their different absorption and emission spectra.[22] These images can be shown on a red-green-blue (RGB) screen. All cartilage samples were examined blindly. The confocal laser microscope was calibrated using a micrometer measured through the objective lens (×4) used for this project. The pixel length measured on images was converted to micrometers. The radiofrequency energy depth and width of penetration were determined in each confocal image of the osteochondral section with Adobe PhotoShop (Adobe PhotoShop, Version 5.0.2, San Jose, California).

The articular surface of the cartilage block cut for scanning electron microscopy was rinsed thoroughly in three changes of normal saline to remove synovial fluid. The 2 × 2 × 2 mm cartilage specimens were fixed in modified Karnovsky's solution (2% glutaraldehyde in 0.1 mol/L sodium cacodylate buffer, pH 7.4) for 2 hours and then washed in 0.1 mol/L sodium cacodylate buffer twice at room temperature. The samples were stored in 0.1 mol/L sodium phosphate buffer for 8 hours at 4°C. The samples were dehydrated in a graded series of ethanol (50%, 70%, 80%, 95%, 100% or absolute), air dried, coated with gold in

a Bio-Rad E5000M gold coater, and examined with a Hitachi S570 scanning electron microscope (Hitachi Ltd., Tokyo, Japan).

Analysis of variance (ANOVA) was used to evaluate the effect of the device on treatment depth, width, and treatment time. When the ANOVA revealed significant differences among groups, a post hoc *t*-test (Duncan's) was performed to analyze the differences. Comparison of the full-thickness penetration of cartilage among devices was performed using Fisher's exact test. Differences were considered to be significant at a probability level of 95% ($P <$ 0.05). All statistical analyses were performed with a commercially available software program (SAS Version 7.1, SAS Institute Inc., Cary, North Carolina).

RESULTS

Thermal smoothing of the abraded cartilage surface was accomplished with all three radiofrequency energy devices when used under arthroscopic visualization in a clinical manner as directed by the manufacturer (Fig. 1). When abraded osteochondral sections were treated via arthroscopy, the ArthroCare and Mitek systems achieved visual smoothing of the articular cartilage 500% and 230% faster than the Oratec system (Table 1). Significant chondrocyte death was observed with each device, and the ArthroCare and Mitek systems penetrated 92% and 78% deeper, respectively, than did the Oratec system (Fig. 2, Table 1). The Mitek and ArthroCare systems penetrated to the level of the subchondral bone in all eight osteochondral sections during the arthroscopically guided paintbrush pattern treatment, while penetration never reached the subchondral bone during treatment with the Oratec system.

All devices produced visual smoothing of the articular cartilage surface (visual examination and scanning electron microscopy analysis) when radiofrequency energy was applied with the mechanical jig in a contact mode. The depth of penetration was 100% deeper for the ArthroCare system and 125% deeper for the Mitek system
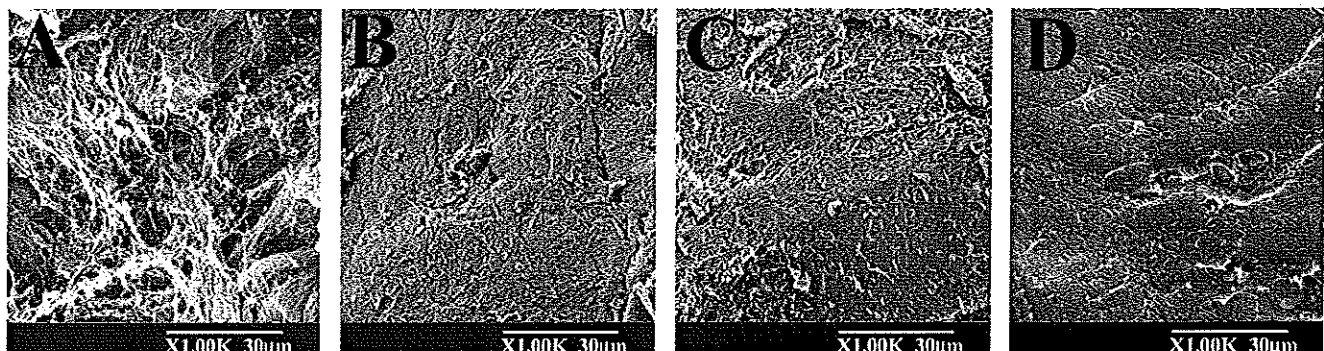
Figure 1. Scanning electron microscopy image of the abraded and radiofrequency energy treated cartilage surface. A, control, the normal cartilage surface was abraded by a custom-made tool. The abraded cartilage surface appears rough with clefts and fibrillation (×1000). B, Oratec monopolar radiofrequency energy treatment, the treated cartilage surface appears smooth and melted (×1000). C, Mitek bipolar radiofrequency energy treatment, the treated cartilage surface appears smooth and melted (×1000). D, ArthroCare bipolar radiofrequency energy treatment, the treated cartilage surface appears very smooth and completely melted (×1000).

TABLE 1
Treatment Time, Subchondral Bone Penetration, and Depth and Width of Chondrocyte Death[§]

Treatment method	Radiofrequency energy system		
	Arthrocare	Mitek	Oratec
Arthroscopically guided treatment, paintbrush pattern			
Time (seconds)	33 ± 5^a	60 ± 6^a	196 ± 20^b
Penetration to subchondral bone (N)	$8/8^a$	$8/8^a$	$0/8^b$
Mechanical jig application, contact mode			
Depth (μm)	1599 ± 86^a	1780 ± 127^a	793 ± 48^b
Width (μm)	5942 ± 264^a	5193 ± 232^a	2602 ± 280^b
Penetration to subchondral bone (N)	$3/8^a$	$3/8^a$	$0/8^b$
Mechanical jig application, noncontact mode			
Depth (μm)	1931 ± 109^a	1498 ± 255^a	No Effect^c
Width (μm)	7368 ± 465^a	4208 ± 454^b	No Effect^b
Penetration to subchondral bone (N)	$7/8^a$	$2/8^b$	$0/8^b$

[§] Values represent means $\pm$ SEM. Values within a row with different letters indicate significant difference ($P < 0.05$).
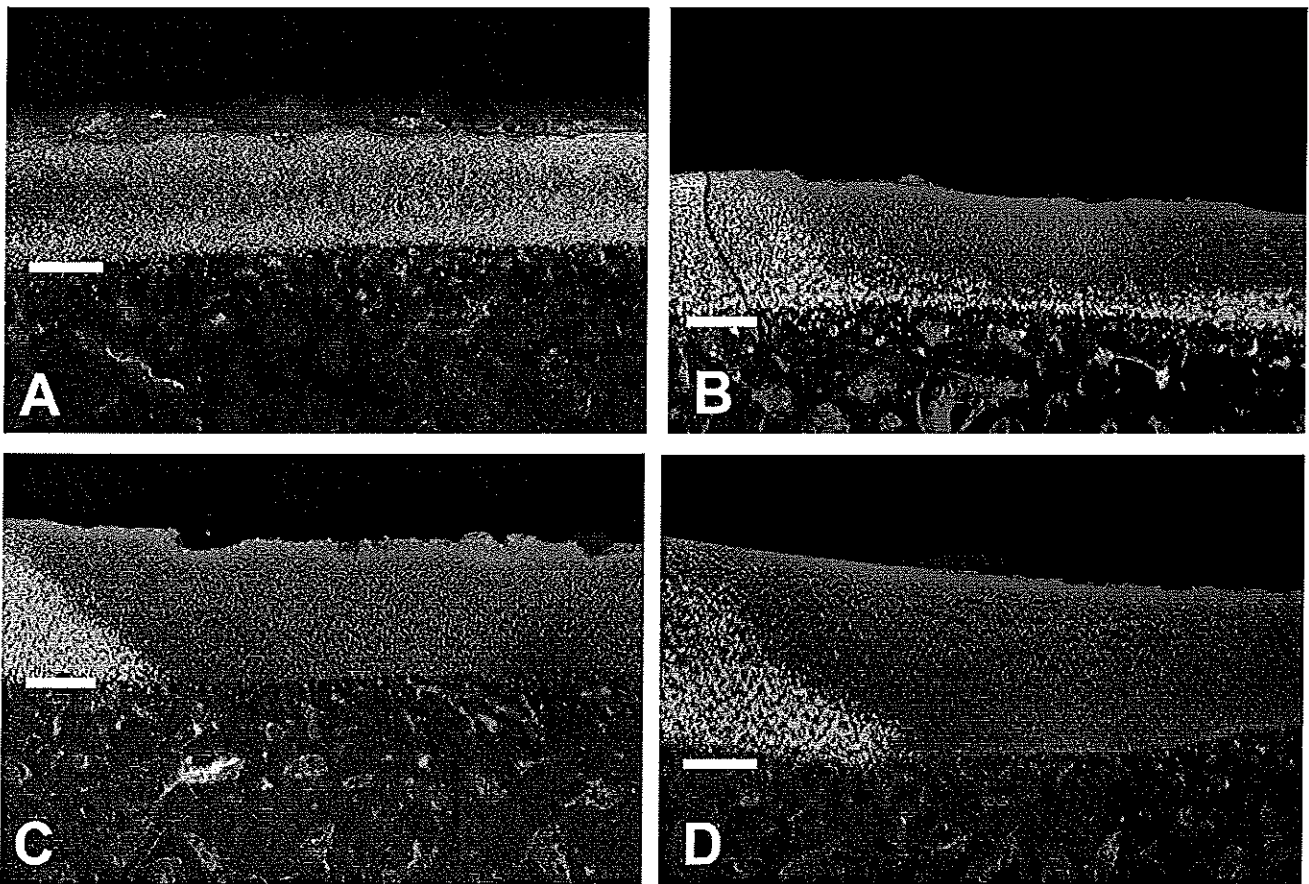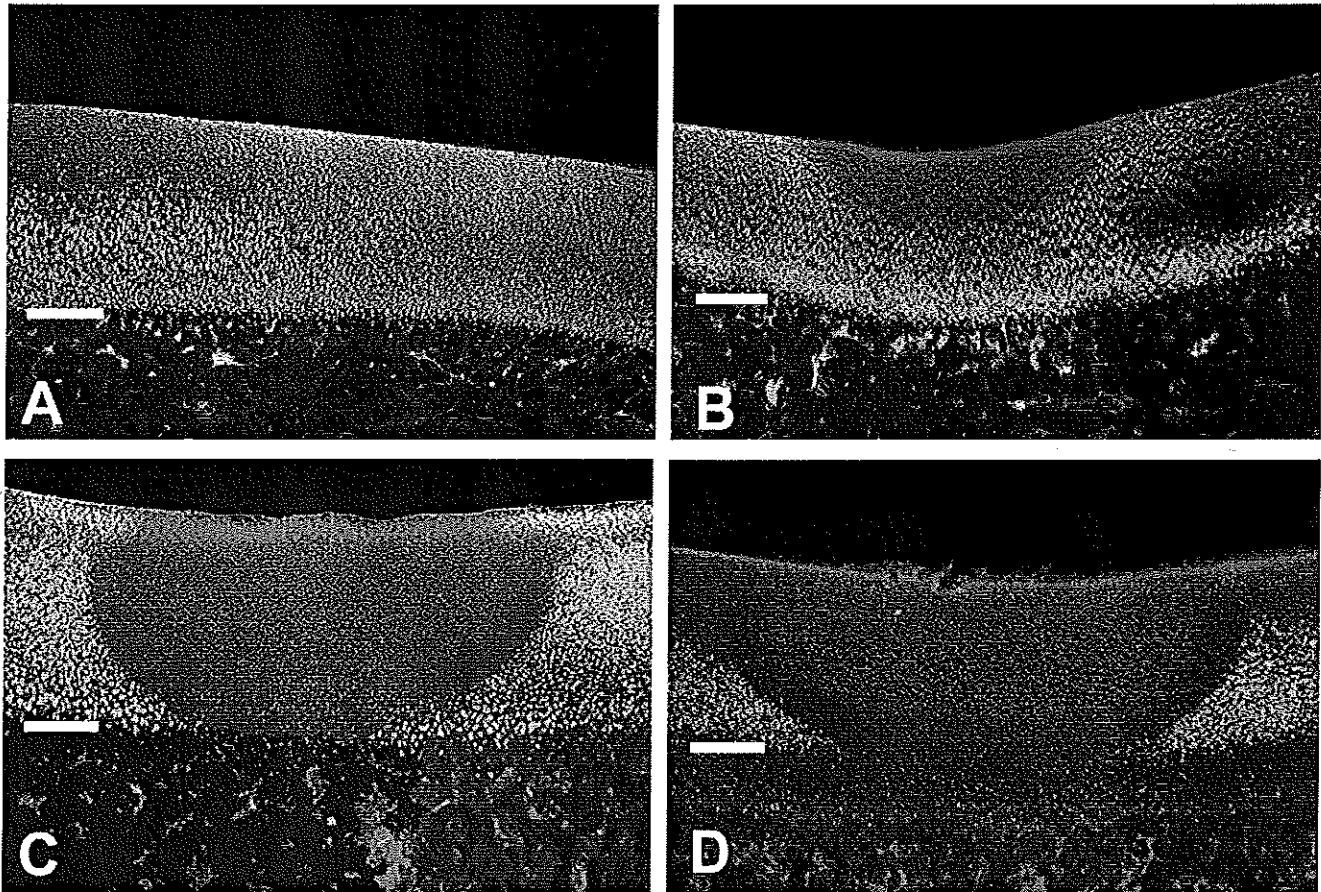

Figure 2. Confocal microscopic image demonstrating radiofrequency energy-treated cartilage surface (top of each image) and subchondral bone (bottom of each image) using paintbrush pattern (original magnification, ×2). The green dots indicate viable chondrocytes and the red dots indicate dead chondrocytes. A, control. B, Oratec monopolar radiofrequency energy treatment caused immediate chondrocyte death and penetration of cell death did not extend to subchondral bone. C, Mitek bipolar radiofrequency energy treatment caused immediate chondrocyte death and penetration of cell death extended to subchondral bone in eight of eight specimens. D, ArthroCare bipolar radiofrequency energy treatment caused immediate chondrocyte death and penetration of cell death extended to subchondral bone in eight of eight specimens. The white bars demonstrate the boundary between the cartilage and subchondral bone.

when compared with the Oratec monopolar system, and the width of chondrocyte death was 128% greater for the ArthroCare system and 100% greater for the Mitek system compared with the Oratec system when all devices were assessed with the mechanical jig in a contact mode (Fig. 3, Table 1). Penetration reached the sub-

Figure 3. Confocal microscopic image demonstrating radiofrequency energy-treated cartilage surface (top of each image) and subchondral bone (bottom of each image) using the mechanical jig in contact mode (original magnification, ×2). The green dots indicate viable chondrocytes and the red dots indicate dead chondrocytes. A, control. B, Oratec monopolar radiofrequency energy treatment caused immediate chondrocyte death and a clear "dead zone" appeared. C, Mitek bipolar radiofrequency energy treatment caused immediate chondrocyte death and a clear dead zone appeared wider and extended to subchondral bone in three of eight specimens. D, ArthroCare bipolar radiofrequency energy treatment caused immediate chondrocyte death and a clear dead zone appeared wider and also extended to subchondral bone in three of eight specimens. The white bar demonstrates the boundary between the cartilage and subchondral bone.

chondral bone in three of eight sections treated with the ArthroCare and Mitek systems, and in none of the sections treated with the Oratec system in a contact mode with the jig ($P < 0.05$).

When evaluated with the jig in a noncontact mode, the ArthroCare and the Mitek systems produced visual smoothing of the articular surface, but there was no effect with the Oratec system used in a noncontact mode. These effects or lack of effect could be seen macroscopically and with scanning electron microscopy. The ArthroCare system penetrated 29% deeper and 75% wider compared with the Mitek system in a noncontact mode. Chondrocyte death extended to the subchondral bone more frequently when using the ArthroCare device (seven of eight sections) than when using the Mitek device (two of eight sections) or the Oratec device (zero of eight sections) ($P < 0.05$) (Fig. 4). When evaluating depth and width of penetration (contact versus noncontact) within devices, the ArthroCare system

penetrated 20% deeper and 25% wider when applied in a noncontact mode compared with a contact mode with the mechanical jig (Table 1). The depth and width of penetration by the Mitek and Oratec devices was either the same or reduced (18% to 100%) when comparing the contact and noncontact modes (Table 1).

DISCUSSION

The experimental protocols of this study were designed to determine the effect of thermal chondroplasty on chondrocyte survival using fresh bovine osteochondral sections from the distal femur treated with either bipolar or monopolar radiofrequency energy systems at the manufacturers' recommended settings. Confocal laser microscopy in conjunction with cell viability staining provided a means of determining the thermal effect of radiofrequency energy on chondrocyte survival in this in vitro study. The study
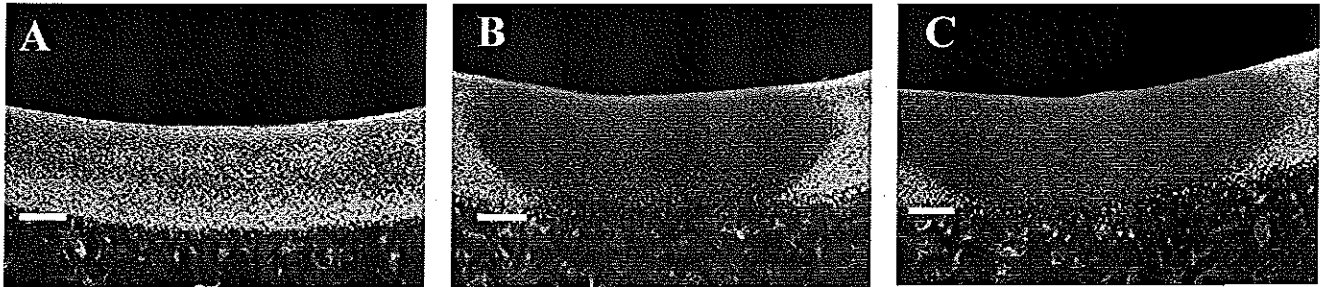
Figure 4. Confocal microscopic image demonstrating radiofrequency energy treated cartilage surface (top of each image) and subchondral bone (bottom of each image) using a mechanical jig in noncontact mode (original magnification, ×2). The green dots indicate viable chondrocytes and the red dots indicate dead chondrocytes. The control specimen is the same as that shown in Figure 3. A, Oratec monopolar radiofrequency energy treatment did not cause immediate chondrocyte death, but no effect was seen on the articular surface. B, Mitek bipolar radiofrequency energy treatment caused immediate chondrocyte death and a clear dead zone appeared wider and extended to subchondral bone in two of eight specimens. C, ArthroCare bipolar radiofrequency energy treatment caused immediate chondrocyte death and a clear dead zone appeared wider and also extended to subchondral bone in seven of eight specimens. The white bar demonstrates the boundary between the cartilage and subchondral bone.

design provided a means to evaluate the effects of radiofrequency energy in a manner similar to the clinical application of radiofrequency energy. During arthroscopic visualization in this study, the bipolar systems were used in a noncontact manner and the monopolar system was used in a contact manner. Use of a mechanical jig for the two methods of application allowed evaluation of the systems without introducing bias by the operator.

Thermal chondroplasty performed with monopolar and bipolar radiofrequency energy systems at the manufacturers' recommended settings achieved macroscopic smoothing of the articular cartilage surface and this was confirmed by scanning electron microscopy. However, treatment resulted in significant chondrocyte death with each radiofrequency energy system evaluated, and in some cases chondrocyte death extended to the level of the subchondral bone. Although these were the manufacturers' recommended settings at the time of the study, the probes, generators, and recommended settings are rapidly evolving based on this and other similar studies. These settings and devices may be modified in the future after further studies are performed in an attempt to determine more optimal settings.

Currently, both monopolar and bipolar radiofrequency energy probes are available for arthroscopic use. The principle of radiofrequency energy heating with a monopolar probe uses an alternating current between the application probe and the grounding plate. This ionic current density produces molecular friction in tissue that results in tissue heating. Frictional or resistive heating of tissue around the probe tip is the primary source of heat, rather than the probe itself.[8,23] The specific amount of energy applied to the tissue and the current path resulting in energy application cannot be specifically determined even under these controlled conditions. When used arthroscopically, the monopolar delivered energy may pass from the probe through the cartilage surface and subchondral bone to the grounding plate on the skin, or from the probe through the irrigation solution to the joint capsule and then to the

grounding plate. The path selected is most likely determined by the impedance encountered as it passes along the cartilage surface and may be influenced by the cartilage thickness, water content, proteoglycan concentration, collagen content, subchondral bone thickness, and the conductive characteristics of the irrigation solution selected. In contrast, energy produced by bipolar probes follows the path of least resistance through a conductive irrigating solution around the probe tip. Consequently, energy application by bipolar radiofrequency energy systems is different from that of monopolar systems.[8] This difference in current path may help explain the difference in depth of penetration between the bipolar devices when evaluated in contact and noncontact modes.

The first reason for increased penetration for the ArthroCare device in a noncontact mode may be related to probe tip design differences between the ArthroCare and Mitek devices, resulting in increased heating at 1 mm from the probe tip with the ArthroCare device. A second explanation for the increased depth of penetration with the ArthroCare device is that use of the probes in a noncontact mode is similar to using a laser in a defocused mode. A larger volume of tissue is heated, and this may allow the tissue to serve as a thermal mass, resulting in increased conductive heating. In addition, using the ArthroCare device in a contact mode may increase the impedance between the anode and cathode of the device and reduce the temperature achieved at equivalent power settings when comparing contact and noncontact modes.

In the past several years, both monopolar and bipolar radiofrequency energy systems have gained popularity for performing soft tissue shrinkage, cutting, and ablation.[8,11,17,21] Turner et al.[25] reported that ablation using bipolar radiofrequency energy resulted in a better outcome than conventional mechanical shaving of abraded articular cartilage in a sheep model. Power settings and energy delivery were not reported in that study. In addition, currently accepted methods for evaluating cell viability were not used, making interpretation of the results