

Thermal Chondroplasty With Bipolar and Monopolar Radiofrequency Energy: Effect of Treatment Time on Chondrocyte Death and Surface Contouring

Yan Lu, M.D., Ryland B. Edwards III, D.V.M., M.S., Shane Nho, B.A., John P. Heiner, M.D., Brian J. Cole, M.D., M.B.A., and Mark D. Markel, D.V.M., Ph.D.

Purpose: The purpose of this study was to evaluate chondrocyte viability and surface contouring of articular cartilage using confocal laser microscopy (CLM) and scanning electron microscopy (SEM), respectively, during different treatment time intervals with monopolar and bipolar radiofrequency energy (RFE). **Type of Study:** In vitro analysis using chondromalacic human cartilage. **Methods:** Forty-two fresh osteochondral sections from patients undergoing partial or total knee arthroplasties were used to complete this study. Each of 36 sections was divided into 2 distinct 1-cm² regions that were treated with either bipolar or monopolar RFE. Six sections were maintained as untreated controls. Six RF treatment time intervals were evaluated: 5, 10, 15, 20, 30, and 40 seconds (6 specimens per time interval per group). After treatment, each specimen was processed for CLM and SEM. **Results:** CLM demonstrated that the depth of chondrocyte death in the monopolar RFE treatment group was significantly less than the bipolar group at each of the same time intervals ($P < .05$). SEM showed that each RFE device began to contour and smooth the articular surface after 15 seconds of treatment. **Conclusions:** When applying thermal chondroplasty, a broad treatment time range could result in variable degrees of cartilage smoothness and significant chondrocyte death. **Key Words:** Articular cartilage—Chondromalacia—Radiofrequency—Confocal laser microscopy—Knee joint—Scanning electronic microscopy.

Thermal chondroplasty with radiofrequency energy (RFE) has garnered widespread interest over the past several years. Currently, there are 2 types of RFE systems available for clinical application: monopolar RFE and bipolar RFE.¹ The treatment time

required to effectively contour chondromalacic cartilage with either RFE system is variable. Typically, surgeons cease RFE treatment when they believe the rough cartilaginous surface is smoothed after subjectively observing it and probing it arthroscopically. We hypothesized that thermal chondroplasty with RFE can cause 2 potential problems. First, RFE may cause full-thickness chondrocyte death to the level of subchondral bone. Second, the surface of chondromalacic cartilage may not be adequately smoothed when treatment is stopped because arthroscopic observation can potentially overestimate the degree of smoothness due to its relatively low magnification.

Several previous studies have addressed treatment time for RFE chondroplasty using in vitro experiments. Kaplan et al.² reported that bipolar RFE (ArthroCare 2000 System; ArthroCare, Sunnyvale, CA) was safe for thermal chondroplasty on human chondromalacic cartilage following a 3-second treatment

From the Comparative Orthopaedic Research Laboratory, Department of Medical Sciences, School of Veterinary Medicine (Y.L., R.B.E., M.D.M.) and the Department of Orthopaedics and Rehabilitation, School of Medicine (J.P.H.), University of Wisconsin-Madison, Madison, Wisconsin; and the Department of Orthopaedic Surgery, Rush Presbyterian Saint Luke's Medical Center, Rush University (S.N., B.J.C.), Chicago, Illinois, U.S.A.

Supported by Smith & Nephew Endoscopy, Menlo Park, California.

Address correspondence and reprint requests to Mark D. Markel, D.V.M., Ph.D., Department of Medical Sciences, School of Veterinary Medicine, University of Wisconsin-Madison, Madison, WI 53706-1102, U.S.A. E-mail: markelm@svm.vetmed.wisc.edu

© 2002 by the Arthroscopy Association of North America

0749-8063/02/1807-2985\$35.00/0

doi:10.1053/jars.2002.32840

interval. Krenzel et al.³ stated that bipolar RFE caused significant chondrocyte death at treatment times over 40 seconds in porcine cartilage. Lu et al.⁴ reported that smoothing of cartilage defects created in normal bovine cartilage required approximately 30 seconds of bipolar RFE and 3 to 4 minutes for monopolar RFE (ORA-50 System; ORATEC Interventions, Mountain View, CA) as determined by visual observations of smoothing by experienced surgeons.

Lu et al.⁵ repeated Kaplan et al.'s study but used confocal laser microscopy (CLM) with vital cell staining to evaluate cell viability. This study revealed that bipolar RFE caused significant chondrocyte death in human chondromalacic cartilage after the identical 3 second treatment time. Despite these important conclusions, some studies suffered from several potential limitations regarding the clinical application of RFE: (1) the samples used were not human cartilage^{3,4}; (2) the cartilage was not chondromalacic cartilage^{3,4}; (3) the treatment patterns used were not the same pattern that is used clinically^{2,3,5}; and (4) power settings were not the manufacturers' recommended settings.^{2,3,5}

To date, no scientific study has reported the effects of either monopolar or bipolar RFE on both chondrocyte death and surface contouring in human chondromalacic cartilage while considering RFE treatment time intervals. The purpose of this study was to evaluate both chondrocyte viability and cartilaginous surface contouring using CLM and scanning electron microscopy (SEM), respectively, during different treatment time intervals with monopolar and bipolar RFE at the manufacturers' recommended settings.^{4,5} Our aim was to provide helpful information to clinicians who use RFE to treat chondromalacic cartilage.

METHODS

All procedures were approved by the Institute Review Board and Human Subjects Committee at participating universities. Forty-two fresh osteochondral sections from 17 patients undergoing total or partial knee arthroplasty were used for this study. The osteochondral sections, placed in physiologic saline (0.15 mol/L) in a sterile container and shipped in a cooler full of ice, were received on the day after knee replacement surgery. The osteochondral sections were treated and analyzed on the same day of receipt. Each of 36 treated sections was divided into 2 distinct 1-cm² regions that were treated with either bipolar or monopolar RFE. Chondromalacia was graded using a modified Outerbridge system^{6,7}: grade 1, softened cartilage surface; grade 2, softened cartilage with fine

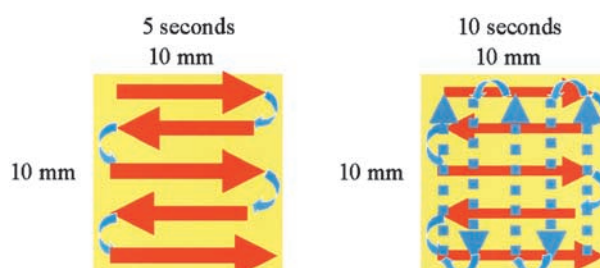


FIGURE 1. RFE treatment pattern used on chondromalacic cartilage at 5- and 10-second treatment time intervals. With treatment times longer than 10 seconds, treatment patterns were repeated. Solid and dotted arrows show the RFE probe pass over the cartilage surface.

fibrillations; grade 3, fibrillated surface with pitting to subchondral bone; and grade 4, fibrillation of cartilage and exposed subchondral bone. Only chondromalacic cartilage of grade 2 was selected for use in this study.

Each specimen was placed on a custom designed jig maintaining a lavage fluid temperature of 22°C. No fluid flow was used during monopolar RFE treatment based on information from a previous study that determined the effect of irrigation fluid flow on cartilage matrix temperatures reached during chondroplasty.⁸ This study showed that monopolar RFE delivered more output power with flow (more heat than during no flow conditions) to maintain the probe tip temperature close to the preset temperature. This was because the probe tip was cooled by the lavage flow.⁸ A flow rate of 120 mL/min was used when applying the bipolar RFE device, approximating the irrigation flow rate used clinically. This flow rate prevents air bubble accumulation within the treatment field and has no positive or negative effect on cartilage matrix temperature.⁸ Under arthroscopic visualization, 2 RFE devices (bipolar and monopolar) designed for musculoskeletal applications were investigated according to the manufacturers' recommended treatment procedures.

The ArthroCare 2000 bipolar RFE System coupled with an Arthrocare CoVac 50° angle probe was used to deliver bipolar RFE in a noncontact fashion (1 mm above cartilage surface) over a 1.0-cm² area in the treatment pattern depicted in Fig 1 at a generator setting of 2 (133 to 147 kHz). The Vulcan EAS coupled with a TAC-C probe (Smith & Nephew Endoscopy, Menlo Park, CA) was used to deliver monopolar RFE in a light contact fashion over a 1.0-cm² area in a treatment pattern identical to that for the bipolar device at a generator setting of 70°C and 15 W. The light contact fashion chosen for monopolar

TABLE 1. SEM Grading System for Chondromalacic Cartilage Surface After RFE Treatment

Surface of Chondromalacic Cartilage	Score
Extremely smooth	3
Relatively smooth with melted fronds	2
Rough and irregular with melted fronds	1
Rough and irregular with fronds	0

NOTE. If a surface was graded to be between 2 scores, the mean of the 2 scores was used (0.5, 1.5, 2.5).

RFE was based on unpublished data from our laboratory showing that that high pressure on the probe tip caused deeper penetration. Six RFE treatment time intervals were evaluated: 5, 10, 15, 20, 30, and 40 seconds. For each radiofrequency generator-treatment time combination, 6 independent samples were used (total, 36 treatments per RFE generator). Another sham-operated group of 6 specimens served as a control. In addition, margins of each treated section served as a control for that section.

After RFE treatment, each treated area was processed for analysis by CLM and SEM. The depth of chondrocyte death was measured using the deepest point of RFE penetration. The CLM processing and evaluation technique has been described in detail.⁵ After evaluation by CLM, the same cartilage sections were trimmed ($3 \times 3 \times 3$ mm) and 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 then were stored in 0.1 mol/L phosphate buffered saline for 8 hours at 4°C. After dehydration in a graded series of ethanol (50%, 70%, 80%, and 100%) and air drying, the samples were coated with gold in an Autoconductavac IV (Seevac, Pittsburgh, PA) gold coater and examined with a Hitachi S570 (Tokyo, Japan) scanning electron microscope.⁹ The image of each section was coded so that the RFE generator and treatment time was unknown and then scored by 3 investigators independently with a custom designed scoring system (Table 1). Higher scores indicate a smoother articular surface.

Mean depth of chondrocyte death for each RFE generator per treatment time combination was compared among groups using analysis of variance (ANOVA; SAS version 7.1; SAS Institute, Cary, NC). Factors included in the analysis were the patient, RFE generator, and treatment time. ANOVA was also used to identify differences between the RFE generators

and among treatment times for the depth of chondrocyte death. Duncan's post hoc analysis was performed when differences among settings were demonstrated by ANOVA. Paired *t* tests were used to identify differences between RFE generators at each treatment time. Patient gender was compared using Wilcoxon signed-rank tests. The interobserver and intraobserver precision errors were determined for the SEM scores. The Kruskal-Wallis test was used to compare the subjective SEM image scores between RFE generators and among treatment times, and among treatment times for each generator. When significance was identified using the Kruskal-Wallis test, the Mann-Whitney procedure was used to compare the subjective scores between groups; *P* < .05 was considered significant.

RESULTS

The age of patients in the bipolar RFE treatment group was 61 ± 6 years (mean \pm standard deviation [SD]; range, 55 to 77 years) and 64 ± 9 years (mean \pm SD; range, 49 to 74 years) in the monopolar RFE treatment group. The thickness of human cartilage used in the bipolar RFE group was significantly thicker (3.2 ± 0.86 mm) than that in monopolar RFE group (2.8 ± 0.73 mm).

During monopolar RFE treatment for the 5- and 10-second treatment time groups, arthroscopic examination showed that the fine fronds protruding from the cartilaginous surface melted, although the clefts still remained and the color of the treated area did not change. In the 15-second treatment time group, the cartilaginous surface became smooth and the color of the treated area changed to light gray. In the 20-, 30-, and 40-second treatment time groups, the cartilaginous surface became smooth and the color of the treated areas changed to light yellow.

During bipolar RFE treatment for the 5- and 10-second treatment time groups, arthroscopy showed that fine fronds melted, although the clefts still remained and the cartilaginous surface appeared slightly rough, with the color of the treated area turning to light yellow. In the 15-second treatment group, the cartilaginous surface became smooth and the color of the treated area changed to yellow. In the 20-, 30-, and 40-second treatment time groups, the cartilaginous surface became smooth and the color of the treated areas ranged from yellow to brown.

CLM showed that monopolar RFE caused significantly less depth of chondrocyte death than bipolar RFE at each treatment time interval (Figs 2, 3, 4).

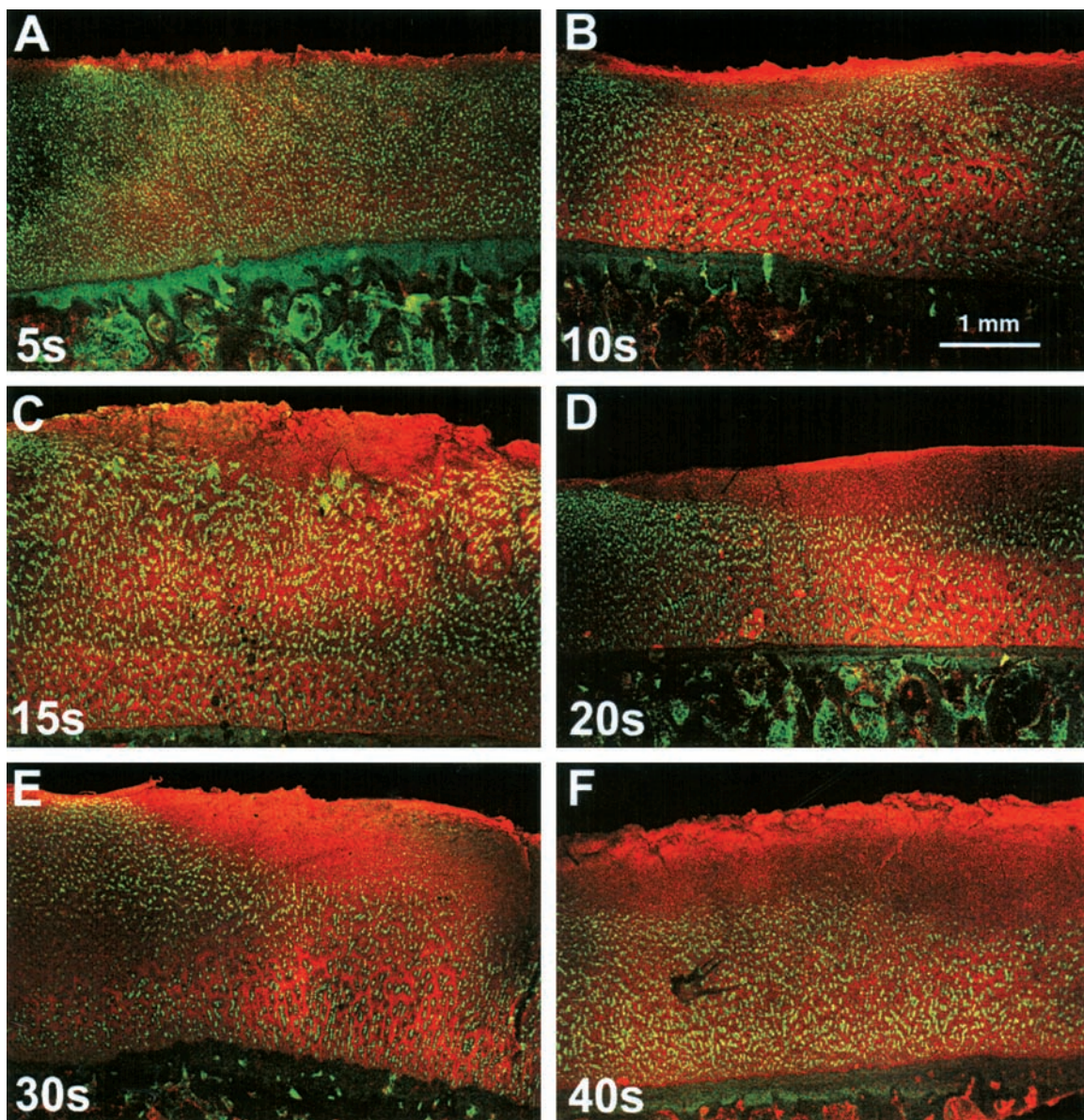


FIGURE 2. Confocal images showing thermal penetration (chondrocyte death) in monopolar RFE treatment groups. Top, cartilage surface; bottom, subchondral bone; green dots, live chondrocytes; red dots, dead chondrocytes. (A) Shows 5 seconds of RFE treatment, (B) 10 seconds of RFE treatment time, (C) 15 seconds of RFE treatment time, (D) 20 seconds of RFE treatment time, (E) 30 seconds of RFE treatment time, and (F) 40 seconds of RFE treatment time. (Original magnification $\times 20$.) (Note that the red region in the areas with green dots is background color; the images were adjusted to appear brighter with high contrast for better image quality.)

Monopolar RFE treatment caused significantly less depth of chondrocyte death in the 5-second group compared with the 10-, 15-, and 20-second groups. In the monopolar RFE group, there were no significant differences in the depth of chondrocyte death among 10-, 15-, and 20-second treatment time groups. Thirty- and 40-second treatment times caused significantly more depth of chondrocyte death than did 10-, 15-, and

20-second times, and 40 seconds caused significantly more depth of chondrocyte death than 30 seconds.

No significant differences in the depth of chondrocyte death were found between 5- and 10-second treatment times after bipolar RFE treatment. Fifteen-, 20-, and 30-second treatments caused significantly more depth of chondrocyte death than 5- and 10-second treatments. The 40-second treatment caused

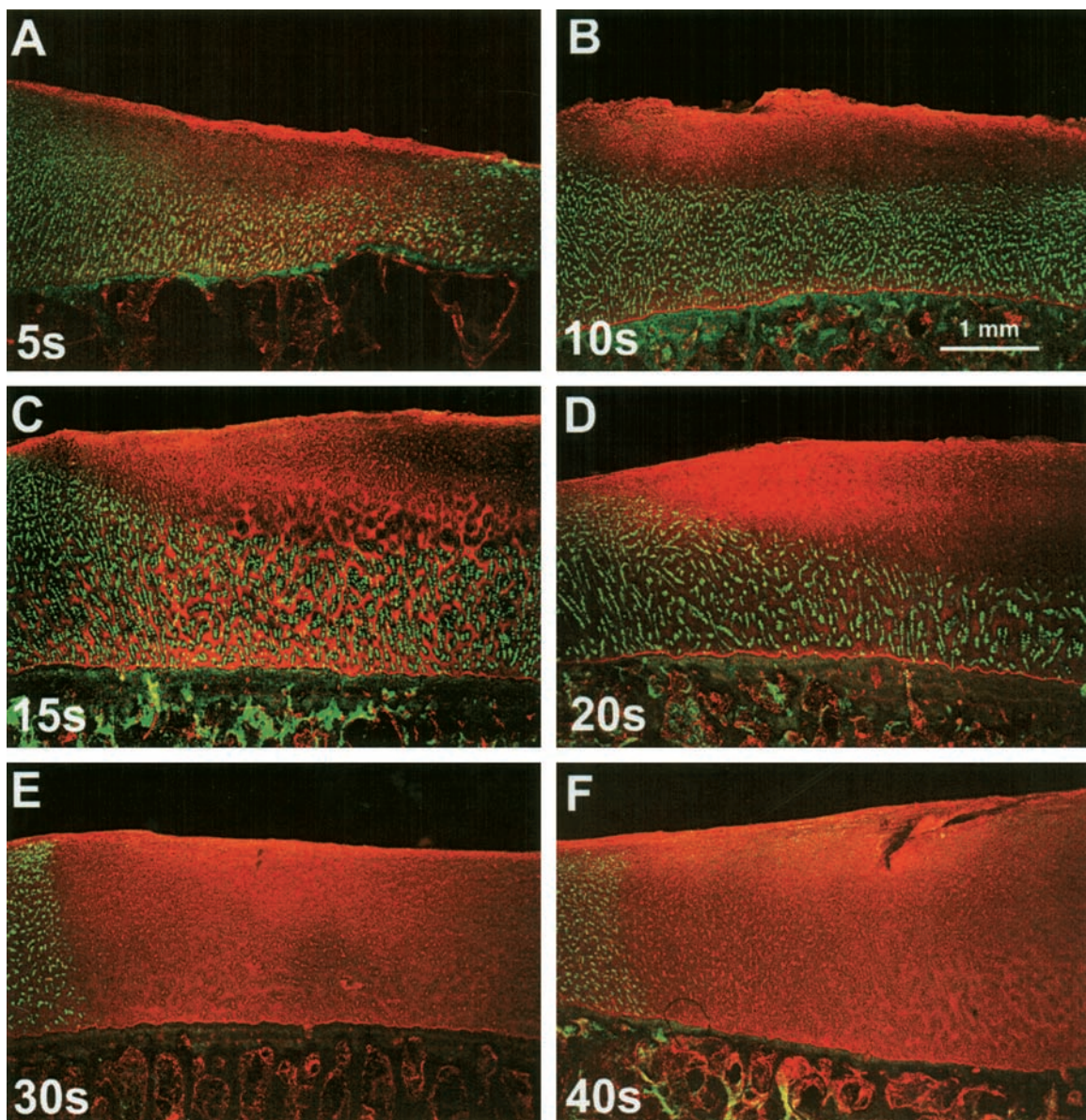


FIGURE 3. Confocal images showing thermal penetration (chondrocyte death) in bipolar RFE treatment groups. Top, cartilage surface; bottom, subchondral bone; green dots, live chondrocytes; red dots, dead chondrocytes. (A) Shows 5 seconds of RFE treatment, (B) 10 seconds of RFE treatment time, (C) 15 seconds of RFE treatment time, (D) 20 seconds of RFE treatment time, (E) 30 seconds of RFE treatment time, and (F) 40 seconds of RFE treatment time. (Original magnification $\times 20$.) (Note that the red region in the areas with green dots is background color; the images were adjusted to appear brighter with high contrast for better image quality.)

significantly more depth of chondrocyte death than the 15-second treatment, but there was no difference in the 20- and 30-second groups.

The intraobserver and interobserver precision errors for SEM scores were 11.4% and 13.8%, respectively. SEM demonstrated that both monopolar and bipolar RFE contoured rough chondromalacic surfaces depen-

dent on treatment time (Figs 5, 6, 7, 8). Analysis of SEM images revealed that both monopolar and bipolar RFE required a minimum of 15 seconds to smooth the cartilage surface sufficiently to reach the SEM score of 2 (relatively smooth, with melted fronds). Monopolar RFE created a smoother surface than bipolar RFE at the 5-second treatment time. There were no signif-

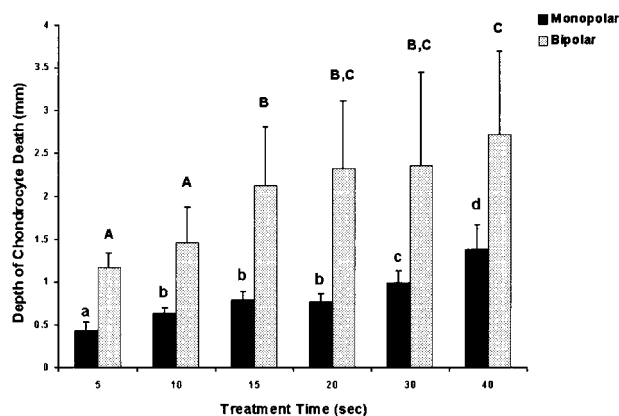


FIGURE 4. Depths of chondrocyte death at different RFE treatment time intervals for both monopolar and bipolar RFE. Bars represent mean \pm SD. Means for a specific probe with different letters are significantly different from each other ($P < .05$). Bipolar RFE caused deeper chondrocyte death than monopolar RFE at each treatment time interval ($P < .05$).

icant differences in surface smoothing between bipolar and monopolar RFE at the remaining treatment time intervals (Fig 8).

For monopolar RFE, the SEM scores of all treatment time groups were significantly higher than the sham-operated control group. SEM scores for 15-second and longer treatment times were significantly higher than those for treatment times of 5 and 10 seconds. There were no significant differences in SEM scores among the groups with treatment times of 15 seconds and longer. For bipolar RFE, SEM scores for the 40- and 30-second treatment time groups were significantly higher than for the 20-second treatment time group; the SEM scores for 20- and 15-second treatment time groups were significantly higher than for 10- and 5-second treatment groups; and the SEM scores for the 10-second treatment time group was significantly higher than that of the 5-second treatment group and the sham-treated group. Unlike monopolar RFE, bipolar RFE application for 5 seconds did not significantly smooth the cartilage surface compared with the sham-operated control.

DISCUSSION

Recently, RFE has become popular as a method of performing chondroplasty.^{2,3} With a bipolar electrode, the RFE follows the path of least resistance between the positive and negative poles of the probe tip through the conductive irrigating solution. Heating occurs at the surface of the active electrode.^{4,10} During monopolar RFE application, the 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.^{4,10-14}

The goal of thermal chondroplasty is to contour the roughened cartilaginous surface while minimizing thermal penetration and depth of chondrocyte death. The outcomes of RFE thermal chondroplasty previously reported have been contradictory. Turner et al.¹⁵ and Kaplan et al.² stated that bipolar RFE was safe for chondroplasty and produced a better histologic appearance than traditional mechanical debridement. Krenzel et al.³ reported that bipolar RFE may kill chondrocytes in large numbers at treatment times of 40 seconds or greater. Lu et al.^{4,9} and Edwards et al.¹⁶ concluded that both monopolar and bipolar RFE may cause significant chondrocyte death, with bipolar RFE causing greater chondrocyte death than monopolar RFE when treating articular cartilage. The current study confirms these previous studies.^{4,9,16}

The SEM results in this study showed that monopolar RFE created a smoother surface than bipolar RFE at the 5-second treatment time. There were no significant differences between monopolar and bipolar RFE at other time intervals. Why does monopolar RFE create a smoother surface than bipolar RFE at the 5-second treatment time when the temperature setting

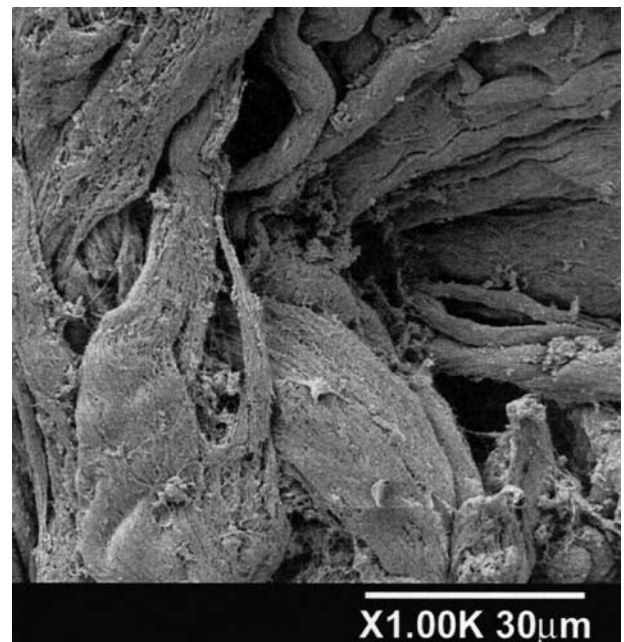


FIGURE 5. SEM image showing sham-operated control cartilage with fibrillated and rough surface (original magnification $\times 1,000$).

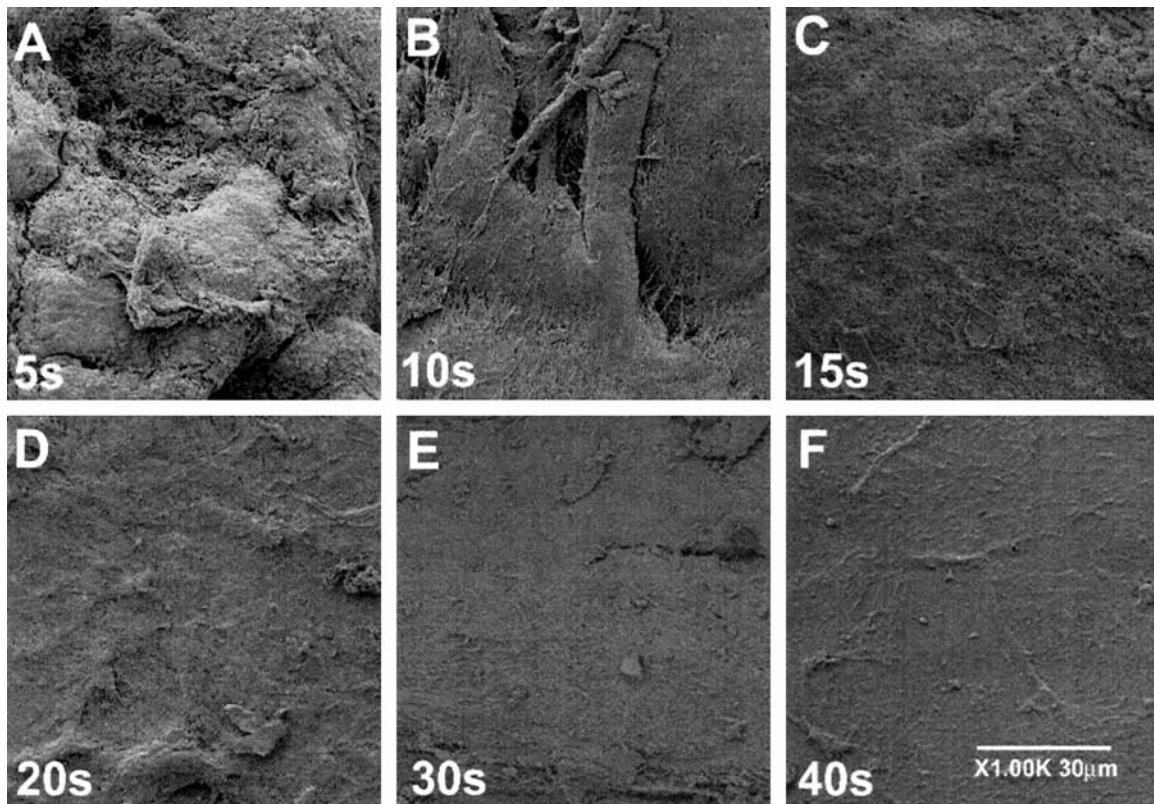


FIGURE 6. SEM images showing the chondromalacic cartilage surfaces treated by monopolar RFE at different treatment time intervals. (A) Shows 5 seconds of RFE treatment, (B) 10 seconds of RFE treatment time, (C) 15 seconds of RFE treatment time, (D) 20 seconds of RFE treatment time, (E) 30 seconds of RFE treatment time, and (F) 40 seconds of RFE treatment time. (Original magnification $\times 1,000$.)

for monopolar RFE is 70°C , which is much lower than bipolar RFE at setting 2 (100°C to 110°C).²² A possible explanation is the different treatment mode used. Monopolar RFE is applied in a light contact mode with no flow. Bipolar RFE is applied in noncontact fashion, approximately 1 mm from the cartilage surface, and fluid flow is used. In the noncontact mode, the bipolar probe must heat the flowing irrigation solution to smooth the cartilage. By 10 seconds, sufficient heating of the irrigation solution and cartilage matrix must have occurred to smooth the cartilage surface similar to the monopolar probe.

The finding that bipolar RFE did not smooth the cartilaginous surface more effectively or faster than monopolar RFE was unexpected. Based on previous studies reporting higher temperatures and greater chondrocyte death with bipolar RFE than with monopolar RFE,^{4,8,16} we assumed that bipolar RFE would smooth the surface both faster and more effectively. Again, a possible explanation for this result is that monopolar RFE was applied in light-contact, no-

flow mode, whereas bipolar RFE was applied in a noncontact, flow mode.

In our SEM grading system for chondromalacic cartilage after RFE treatment, a score of 2 is defined as the minimal score required for a relatively smooth surface. In this study, both monopolar and bipolar RFE took at least 15 seconds to contour the chondromalacic human cartilage to a score of 2. Five- and 10-second application times for either monopolar or bipolar RFE resulted in an articular surface that remained rough and irregular, with fronds that were melted but incompletely contoured.

As expected, when CLM and SEM results are combined, this study shows that there is a trade-off between chondrocyte death and RFE treatment time. The mean depth of chondrocyte death at 5- and 10-second treatment times ranged from 0.45 to 0.65 mm for monopolar RFE and from 1.1 to 1.5 mm for bipolar RFE. However, at these treatment times, the cartilage surfaces do not meet our definition of a relatively smooth surface. At the 15-second treatment time, the

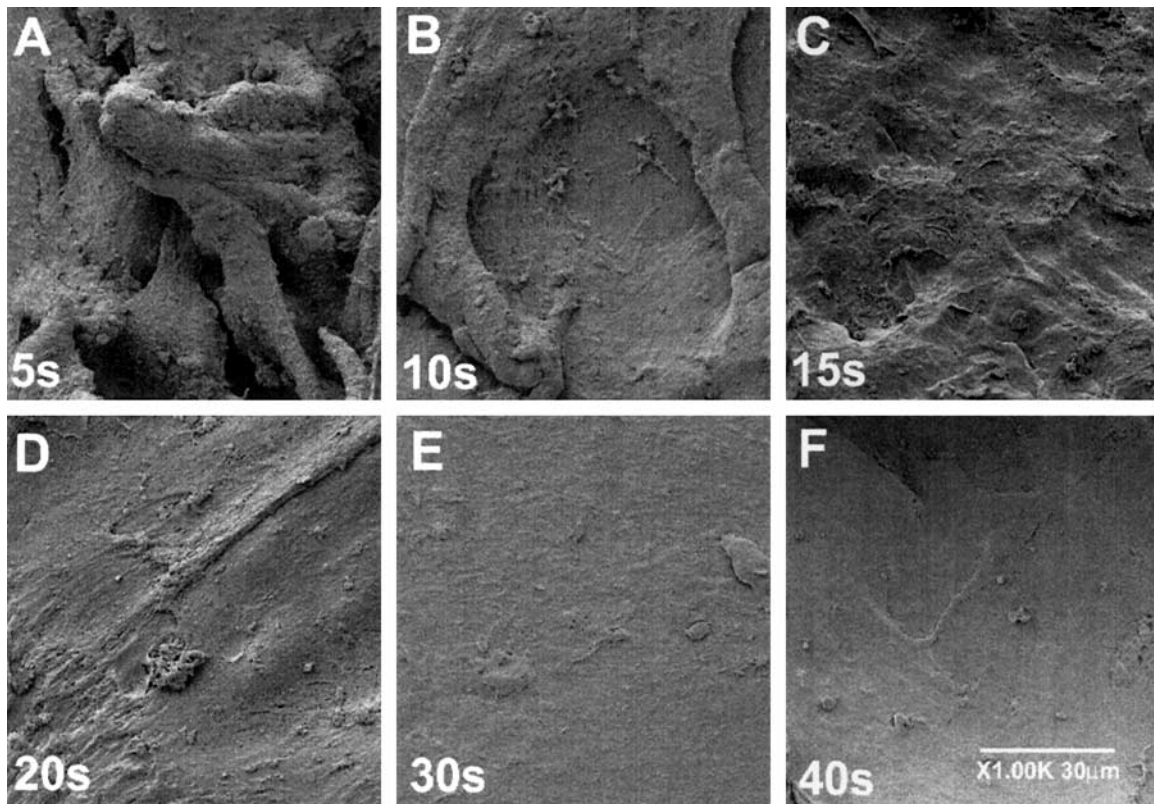


FIGURE 7. SEM images showing the chondromalacic cartilage surfaces treated by bipolar RFE at different treatment time intervals. (A) Shows 5 seconds of RFE treatment, (B) 10 seconds of RFE treatment time, (C) 15 seconds of RFE treatment time, (D) 20 seconds of RFE treatment time, (E) 30 seconds of RFE treatment time, and (F) 40 seconds of RFE treatment time. (Original magnification $\times 1,000$.)

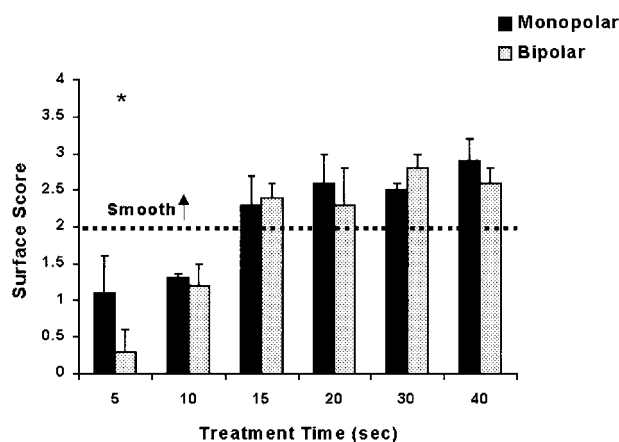


FIGURE 8. SEM scores for the surface of monopolar and bipolar RFE at different treatment time intervals. Higher scores indicate smoother surface. The dotted line at surface score 2 is a standard for cartilage surface smoothing. Score values represent the means of 3 observers \pm SD. Means with asterisks are significantly different from each other at each time interval ($P < .05$).

cartilage surface was optimally contoured, but the depth of chondrocyte death was 0.79 ± 0.1 mm for monopolar RFE (mean \pm SD) and was 2.1 ± 0.6 mm (mean \pm SD) for bipolar RFE. These findings should be considered in context of the thickness of normal human knee cartilage of 1.9 mm for the femur, 1.9 mm for the tibia, and 2.0 for the patella.¹⁷ The thickness of chondromalacic human knee cartilage typically is 2.0 mm for the femur, 2.2 mm for the tibia, and 3.7 mm for the patella.¹⁸ The results of this study show that bipolar RFE should be used to treat chondromalacic cartilage with extreme caution, if at all, because treatment times of 15 seconds or longer are required to smooth the cartilage surface but these times may result in full-thickness chondrocyte death in some cases.

Compared with a previous study,⁴ this study revealed that the depth of chondrocyte death after bipolar RFE treatment (Covac 50° probe) for 5 seconds at

setting 2 was less than that for 3 seconds at setting 2 in a previous study (1.17 mm v 1.9 mm). There are likely 2 major reasons for this difference. First, the lavage temperature used was different in the 2 studies. The lavage temperature used in the current study was 22°C whereas 37°C was used in the previous study. In the noncontact mode, bipolar RFE would heat the lavage solution around the probe tip first and then heat the cartilage through the heated lavage solution. With 37°C lavage solution, the solution heats more quickly, causing cartilage to reach higher temperatures faster than in 22°C lavage solution. Second, the treatment time was different. In the previous study, bipolar RFE was applied linearly over a 1-cm pass for 3 seconds. In the current study, bipolar RFE was applied over a 1-cm pass for just 1 second (5 passes covering a 1-cm² area for 5 seconds). Therefore, the treatment time in the previous study was 3 times longer than in the current study. Future studies investigating the effects of hypothermic lavage solution on thermal chondroplasty with bipolar RFE need to be conducted.

Several limitations of this study require discussion. First, this study was performed in vitro and our results may not be applicable to in vivo conditions. Second, the human cartilage samples included in this study were Outerbridge grade 2, without thick flaps or deep clefts that could require greater treatment times to smooth. Third, surgeons use RFE to smooth rough cartilage surfaces as judged subjectively through arthroscopic visualization and probing at a relatively low magnification ($\sim \times 2$ to 4). As compared with SEM, arthroscopy may overestimate the degree of smoothing. A future study comparing arthroscopic estimation of smoothing to our SEM grading system could enhance the present study by elucidating the clinical relevance of the SEM grading system. Fourth, in this study, monopolar RFE was applied in light contact without flow and bipolar RFE was applied in noncontact with flow. We acknowledge that direct comparison between the applications of these 2 RFE devices using different treatment modes is problematic. The reason we performed this comparison using different treatment conditions was to conform to both the manufacturers' recommendations for use and how surgeons use the devices clinically.

In this study we found that bipolar RFE caused significantly greater chondrocyte death than monopolar RFE at identical treatment time intervals, confirming the findings of previous studies.^{1,6,7,12} This study also showed that it took at least 15 seconds for both bipolar and monopolar RFE to contour a 1-cm² chondromalacic cartilaginous surface to a relatively

smooth surface, as shown by SEM. When thermal chondroplasty is applied clinically, a broad treatment time range may result in variable degrees of cartilage smoothness and potentially significant chondrocyte death.

Acknowledgment: The authors thank John Bogdanske and Megan Coveyou for their assistance with this project. The authors also wish to thank Lance Rodenkirch for his confocal expertise and Philip Oshel for his SEM expertise. The confocal microscope at the University of Wisconsin Medical School was purchased with a generous gift from the W. M. Keck Foundation. The authors would like to thank Drs. Mitchell B. Sheinkop, Aaron Rosenberg, and Richard A. Burger for allowing us access to fresh articular cartilage specimens obtained during knee replacement surgery. Partial funding support for Shane Nho was provided by an Alpha Omega Alpha Research Fellowship.

REFERENCES

1. Edwards RB, Markel MD. Radiofrequency energy treatment effects on articular cartilage. *Oper Tech Sports Med* 2001;11:96-104.
2. Kaplan L, Uribe JW, Sasken H, Markarian G. The acute effects of radiofrequency energy in articular cartilage: An in vitro study. *Arthroscopy* 2000;16:2-5.
3. Krenzel BA, Mann CH, Kayes AV, Speer KP. The effects of radiofrequency ablation on articular cartilage: A time dependent analysis. Proceedings of the 67th Annual Meeting of American Academy of Orthopaedic Surgeons, Orlando, FL, March 2000;1:592.
4. Lu Y, Edwards RB, Cole BJ, Markel MD. Thermal chondroplasty with radiofrequency energy: An in vitro comparison of bipolar and monopolar radiofrequency devices. *Am J Sports Med* 2001;29:42-49.
5. Lu Y, Edwards RB, Kalscheur VL, et al. Effect of bipolar radiofrequency energy on human articular cartilage: Comparison of confocal laser microscopy and light microscopy. *Arthroscopy* 2001;17:117-123.
6. Curl WW, Krome J, Gordon ES, et al. Cartilage injuries: A review of 31,516 knee arthroscopies. *Arthroscopy* 1997;13:456-460.
7. Lonner BS, Harwin SF. Chondromalacia patellae: Review paper. Part I. *Contemp Orthop* 1996;32:81-85.
8. Edwards RB, Lu Y, Rodriguez E, Markel MD. Thermometric determination of cartilage matrix temperatures during thermal chondroplasty: Comparison of bipolar and monopolar radiofrequency devices. *Arthroscopy* 2002;18:339-346.
9. Lu Y, Hayashi K, Hecht P, et al. The effect of monopolar radiofrequency energy on partial-thickness defects of articular cartilage. *Arthroscopy* 2000;16:527-536.
10. Shellock FG, Shields J. Temperature changes associated with radiofrequency energy-induced heating of bovine capsular tissue: Evaluation of bipolar RF electrodes. *Arthroscopy* 2000;16:348-358.
11. Haines DE, Watson DD, Verow AF. Electrode radius predicts lesion radius during radiofrequency energy heating: Validation of a proposed thermodynamic model. *Circ Res* 1990;67:124-129.
12. Nath S, DiMarco JP, Haines DE. Basic aspects of radiofrequency catheter ablation. *J Cardiovasc Electrophysiol* 1994;5:863-876.
13. Nath S, Haines DE. Biophysics and pathology of catheter

- energy delivery systems. *Prog Cardiovasc Dis* 1995;37:185-204.
14. Nath S, DiMarco JP, Mounsey JP, et al. Correlation of temperature and pathophysiological effect during radiofrequency catheter ablation of the AV junction. *Circulation* 1995;92:1188-1192.
 15. Turner AS, Tippet JW, Powers BE, et al. Radiofrequency (Electrosurgical) ablation of articular cartilage: A study in sheep. *Arthroscopy* 1998;14:585-591.
 16. Edwards RB III, Lu Y, Kalscheur VL, et al. Thermal chondroplasty of chondromalacic human cartilage: An ex vivo comparison of bipolar and monopolar radiofrequency devices. *Am J Sports Med* 2002;30:90-97.
 17. Adam C, Eckstein F, Milz S, et al. The distribution of cartilage thickness in the knee-joints of old-aged individuals measurement by A-mode ultrasound. *Clin Biomech* 1998;13:1-10.
 18. Kladny B, Martus P, Schiwy-Bochat KH, et al. Measurement of cartilage thickness in the human knee joint by magnetic resonance imaging using a three-dimensional gradient-echo sequence. *Int Orthop* 1999;23:264-267.