ORIGINAL ARTICLE
pISSN 2234-778X • eISSN 2234-5248
J Minim Invasive Surg 2022;25(3):106-111

JMIS Journal of Minimally Invasive Surgery

Capacitive coupling leading to electrical skin burn injury during laparoscopic surgery

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Purpose: Trocar-site burns occurring during laparoscopic surgery have been reported in various cases, and several efforts to reduce them are underway. This study aimed to analyze the effect of capacitive coupling on trocar site by observing electrical and histological changes for electrical skin burn injury.

Methods: To measure the electrical changes relating to capacitive coupling, the temperature, current, voltage, and impedance around the trocar were measured when an open circuit and a closed circuit were formed using insulation intact instruments and repeated after insulation failure. After the experiment, the tissue around the trocar was collected, and microscopic examination was performed.

Results: When open circuits were formed with the intact insulation, the impedance was significantly reduced compared to the cases of closed circuits (142.0 Ω vs. 109.3 Ω, $p = 0.040$). When the power was 30 W and there was insulation failure, no significant difference was measured between the open circuit and the closed circuit (147.7 Ω vs. 130.7 Ω, $p = 0.103$). Collagen hyalinization, nuclear fragmentation, and coagulation necrosis suggesting burns were observed in the skin biopsy at the trocar insertion site.

Conclusion: This study demonstrated that even with a plastic trocar and electrosurgical instruments that have intact insulation, if an open circuit is formed, capacitive coupling increases, and trocar-site burn can occur. When using electrocautery, careful manipulation must be taken to avoid creating an open circuit to prevent capacitive coupling related to electrical skin burn.

Keywords: Electric burns, Electrocoagulation, Laparoscopy, Surgical instruments, Wounds and injuries

Received August 26, 2022
Revised September 1, 2022
Accepted September 12, 2022

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INTRODUCTION

In the laparoscopic approach, monopolar electrosurgery is essential. Complications related to monopolar electrosurgery involve several mechanisms, such as direct coupling, insulation failure, and capacitive coupling [1]. Educational recommendations and clinical efforts are conducted to reduce the complications relating with electrocautery. At present, instead of the metal trocars, plastic trocars are used in most cases because unintentional contact with electrosurgical instruments can cause electrical tissue damage [2]. When using an electrosurgical instrument, activation before tissue contact can elevate abruptly electrical power (watt) to increase the risk of unintended electrical injury; it is called as an open circuit. Therefore, to reduce the electrical damage, using an instrument that can form a closed circuit was recommended [1,3].

Insulation failure is a major cause of uninduced bowel injury during laparoscopic abdominal surgery [4,5] and can lead to serious consequences. Specifically, during laparoscopic surgery, it can cause bowel injury in an area outside the surgeon's field of view, leading to fatal results such as delayed bowel perforation and peritonitis. Thus, to prevent insulation failure related complications, disposable devices are used or checks for insulation failure are performed in advance. Moreover, thermal injury has also been reported at the trocar insertion site after using an electrosurgical instrument [6,7]; it was considered to be caused by electrical damage due to insulation failure with direct coupling or capacitive coupling. Capacitive coupling is defined as the current transferred from the active electrode through intact insulation to the adjacent conductive material without direct contact [8].

This study aimed to analyze the capacitive coupling effect on trocar site by observing electrical and histological changes when a closed circuit and an open circuit are formed in laparoscopic surgery. Furthermore, the effect of the insulation failure on the formation of capacitive coupling was evaluated for electrical skin burn injury.

MATERIALS AND METHODS

Current, voltage, and impedance were measured using a multimeter (287 True-RMS multimeter; Fluke, Everett, WA, USA), and temperature was measured using a thermometer (566 IR thermometer, Fluke). An electrosurgical generator (Force FX-9c; Valleylab, Minneapolis, MN, USA) and 5-mm plastic trocars (Laport-MU; Sejong Medical, Paju, Korea) were used in the experiment.

A 12-mm plastic trocar was installed in the navel of the pig for the camera, and then two 5-mm plastic trocars were inserted into the right and left abdominal walls of the pig. A device with intact insulation was introduced through a 5-mm trocar. After attaching the tip of electrocautery to the small intestine in the abdominal cavity, the temperature, voltage, current, and impedance around the trocar were measured while cutting the small intestine wall with 30 W of power in the coagulation mode for 30 seconds (closed circuit). The same items were measured by activating the electrocautery at distance of approximately 5 cm from the wall of the small intestine for 30 seconds with 30 W of power in the coagulation mode (open circuit) (Fig. 1).

To measure the electrical change relating to the insulation condition of laparoscopic instruments, the insulation layer of the device was intentionally scratched to make a failed insulation condition. Electrical experiments were performed under intact and failed insulation conditions. All electrical experiment processes were repeated six times in the same manner. To induce electrical skin burn, electrocautery with a power of 30 W was activated for 10 minutes through a 5-mm trocar. After removing the trocar, the skin into which it entered was excised. After fixing the tissue in 10% formalin solution, paraffin blocks were prepared at intervals of 5 mm and stained with hematoxylin and eosin. Pathologic analysis was performed to evaluate skin tissue change from the epidermis to the subcutaneous fat layer that was related to electrical skin burn.

Statistical analysis was performed on the measured data using an independent sample t-test with IBM SPSS for Windows, version 25 (IBM Corp., Armonk, NY, USA). Significance was set at $p < 0.05$.

RESULTS

The electrical characteristics were organized by dividing the four items, namely, skin temperature, current, voltage, and impedance, around the trocar into closed and open circuits (Table 1).

When open circuits were formed with the intact insulation, the impedance was significantly reduced compared to the cases

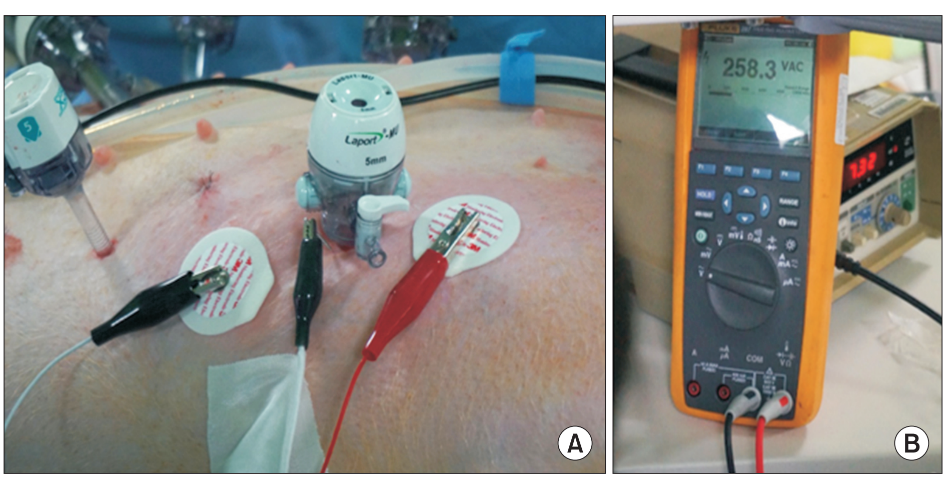

Fig. 1. Measuring electrical indicators. (A) Electrodes are attached around the plastic trocar to measure current, voltage, and impedance. Each experiment was repeated in four trocars except for the trocar in which the laparoscopic camera was inserted. (B) This is the Fluke-287 True-RMS multimeter (Fluke, Everett, WA, USA) used at the time of the experiment.

of closed circuits (142.0 Ω vs. 109.3 Ω, $p = 0.040$). No significant differences were found in the temperature, current, and voltage between the two groups. When the power was 30 W and there was insulation failure, no significant difference was measured between the open circuit and the closed circuit (147.7 Ω vs. 130.7 Ω, $p = 0.103$). Likewise, no significant differences were observed in the temperature, current, and voltage between the two groups (Fig. 2).

Table 1. Analysis of changes in temperature, current, voltage, and impedance in closed and open circuits

Variable	Closed circuit	Open circuit	*p* value
Intact insulation			
Skin			
Temperature (ºC)	31.8	31.6	0.330
Current (mA)	79.0	62.3	0.175
Device			
Voltage (mV)	183.0	220.0	0.104
Impedance (Ω)	142.0	109.3	0.040*
Insulation failure			
Skin			
Temperature (ºC)	31.3	31.1	0.719
Current (mA)	68.3	63.7	0.193
Device			
Voltage (mV)	210.7	218.3	0.371
Impedance (Ω)	147.7	130.7	0.103

The power of the electrosurgical instruments remained the same at 30 W. When the insulation was intact, an open circuit was formed, and a significant decrease in impedance occurred. In the case of insulation failure, no significant difference was found between the open circuit and the closed circuit.
*$p < 0.05$.

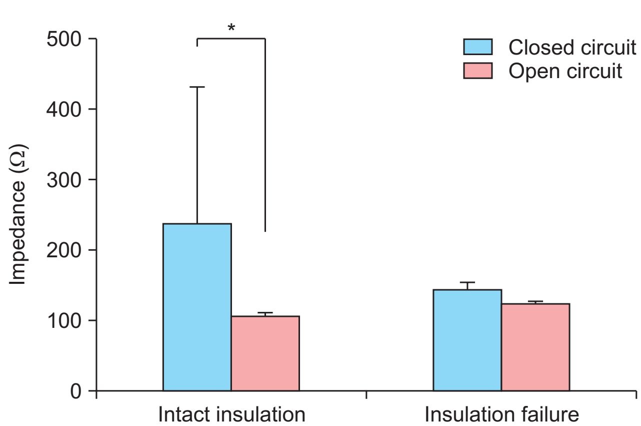

Fig. 2. Impedance changes in closed and open circuits. When the insulation is intact, the decrease in impedance was significantly observed (*$p < 0.05$).

Collagen hyalinization was observed in the biopsy performed at the trocar insertion site, and nuclear fragmentation and coagulation necrosis suggesting electrical burns were observed. Also, fat degeneration was observed in subcutaneous fat layer (Fig. 3).

DISCUSSION

Impedance has an inverse relationship with capacitance (Fig. 4), that is, as the capacitive coupling increases, the impedance decreases. In the case with a power of 30 W and intact insulation, a significant decrease in impedance in the open circuit indicates an increase in capacitive coupling. Because increased capacitive coupling is related to burns [9], this experiment showed that electrical skin burns can occur when the material of the trocar is plastic and the insulation of the electric cauterizer is intact. In the case with a power 30 W and insulation failure, no significant difference was noted in impedance, which shows that the risk of electrical burns around the trocar was lower in the case of insulation failure.

This is the opposite of what was expected. Surgeons assume that burns will not occur if they have a plastic trocar and electrosurgical instrument with intact insulation. However, contrary to expectations, if there is insulation failure, the impedance change around the trocar is insignificant because the current is transmitted through the place where insulation failure occurs. When the insulation is intact, because both the insulation and the plastic trocar act as non-conductors, the current accumulates in the skin where the trocar is inserted owing to capacitive coupling. Electrical burns occur at the trocar site because of this electrical change.

In the presence of insulation failure, the risk of intestinal perforation in the abdominal cavity increases [3,4]. Although intestinal damage caused by insulation failure is a complication of current caused by direct contact (closed circuit), trocar-site burn due to capacitive coupling occurs when an open circuit is formed. Therefore, when the surgeon activates the instrument for electrical cauterization, tissue contact helps prevent trocar-site burns. In the case of intact insulation, even if a part other than the activated cauterizer comes into contact with the field outside the field of view, the current is not transmitted by the insulation. Therefore, because intestinal damage is not possible, it is reasonable to activate the electric cauterizer while maintaining a closed circuit.

Capacitive coupling that occurs in laparoscopic surgery can be thought of simply as capacitance in a cylindrical capacitor (Fig. 4). If the inner cylinder is regarded as an electrosurgical instrument and the outer cylinder is considered the skin surface where

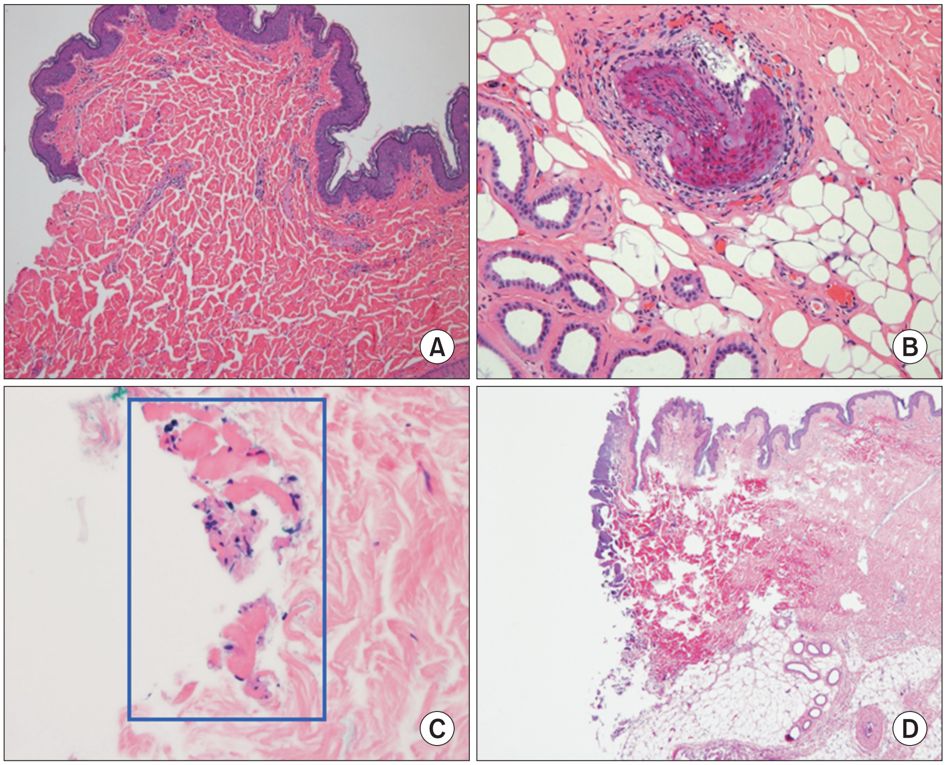

Fig. 3. Tissue slide photo of the skin surrounding the trocar. At the end of the experiment, the tissue at the trocar insertion site was collected, and hematoxylin and eosin staining was performed. (A) Collagen hyalinization. (B) Collagen hyalinization and hair follicle cell vacuolization. (C) Nucleus fragmentation and coagulation necrosis in the blue box. (D) Strong staining in the electrical damage area from the epidermis to the subcutaneous fat layer.

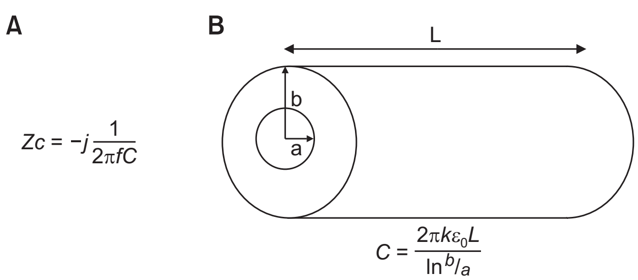

Fig. 4. Formulas related to capacitive coupling. (A) Impedance of a capacitor equation. *Zc*, impedance of a capacitor; *f*, frequency of the signal; *C*, capacitance of the capacitor. (B) Coaxial cylindrical capacitor and its capacitive coupling formula. *C*, capacitance; *a*, radius of the inner cylinder; *b*, radius of the outer cylinder; *L*, length of the cylinder; *k*, dielectric constant; ε_0, permittivity of vacuum.

the trocar is inserted, the capacitance is inversely proportional to the distance from the center to the skin surface. This was determined according to the incision size of the trocar insertion site. In this study, as there was no control for incision size, the effect could not be examined; however, in a subsequent study, the related effect should be analyzed. The strength of study lies in that it is the first to examine the presence or absence of insulation, among the factors associated with burns occurring at trocar sites. In previous studies, capacitive coupling was reported to increase as the generator power setting increased when the electric cauterizer was in the coagulation mode, and the activation time increased [6]. Disposable instruments are recommended to prevent complications caused by insulation failure [1]. In such cases, care must be taken to avoid forming an open circuit.

We experienced a case of trocar-site burn after laparoscopic low anterior resection for a rectal cancer patient. When the patient was observed until 4 days after surgery, wound healing was delayed, and scars remained even after wound healing was completed (Fig. 5). This study is meaningful because the electrical causes of the clinical situation such as trocar-site skin burn were explored using an in vivo experiment.

One limitation of this study is that the activation time of the electrosurgical instrument was limited to 10 minutes. In actual surgery, an electric cauterizer such as Bovie is used through a trocar for a short period of 1 hour to a maximum of 4 hours or more. This means that an electric current similar to that in an actual clinical trial could not be maintained. However, because this study directly measured the electrical properties around the trocar, the effect of capacitive coupling on the tissue could be numerically observed. The existence of the difference in electrical properties means that if the activation time is as long as the actual operation time, the effect of the electric current will be continuously applied and histological changes will occur more clearly. A follow-up study that increases the activation time of electrocautery to induce a situation similar to that of actual clinical practice is necessary.

Fig. 5. Photographs of trocar-site skin after laparoscopic low anterior resection (LAR) surgery. (A) The trocar-site skin burn was found just after laparoscopic LAR. (B) On the postoperative day (POD) 4 of the same patient, the wound healing process progressed slowly, and a discolored wound scar was observed. (C) Trocar-site skin burn was not found on POD 0 after laparoscopic LAR with the proper skin incision and prohibition of open circuit activation in another patient. The photos were taken after obtaining informed consent from the patients.

Even if a plastic trocar and an electric cauterizer with intact insulation were used, the tendency of capacitive coupling increased when an open circuit was formed. When a disposable electrosurgical instrument is used, insulation is expected to be intact. Therefore, when using disposable devices, care must be taken to avoid creating an open circuit. When using recyclable instruments, more attention should be paid to direct coupling with bowel injury caused by insulation failure rather than trocar-site burns due to capacitive coupling. In the future, an experimental study on the additional direction to reduce burns in the case of intact insulation is necessary.

In conclusion, this study demonstrated that even with a plastic trocar and electrosurgical instruments that have intact insulation, if an open circuit is formed, capacitive coupling increases, and trocar-site burn can occur. When using disposable devices, care must be taken to avoid creating an open circuit to prevent electrical skin burns.

NOTES

Ethical statements

This study was approved by the Institutional Animal Care and Use Committee at Pusan National University Hospital (No. PNUYH-2018-60).

Authors' contributions

Conceptualization: GMS
Methodology: All authors
Investigation: MSK, GMS, SUY, GRJ, DHS, JYK, KRB
Formal analysis: WJK, MSK, GMS
Project administration: IYL, MSK, GMS
Writing–original draft: WJK, GMS
Writing–review & editing: All authors
All authors read and approved the final manuscript.

Conflict of interest

All authors have no conflicts of interest to declare.

Funding/support

None.

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