Original Article

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Computed Tomography-Assisted Minimally Invasive Transforaminal Lumbar Interbody Fusion in a Hybrid Operating Room: Preliminary Experience at the E-Da Cancer Hospital

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Objective: Minimally invasive transforaminal lumbar interbody fusion (MI TLIF) is a mainstream surgical procedure for degenerative lumbar diseases. Misplacement of percutaneous pedicle screws is a risk that may cause nerve root injury. Intraoperative computed tomography (CT) scanning can detect misplaced screws and decrease implant errors during surgery. We report our experience of performing CT-assisted MI TLIF in the hybrid operating room (OR) of the E-Da Cancer Hospital.

Methods: Twenty patients were reviewed. Following microsurgical decompression and C-arm fluoroscope-guided implantation of fusion cages and pedicle screws, intraoperative CT scanning was performed. Images were evaluated by operating surgeons immediately.

Results: Among 118 implanted lumbar and sacral screws, 4 misplaced lumbar pedicle screws were detected by intraoperative CT, and replaced during surgery. All patients reported improvement of their presenting symptoms after surgery. None of them needed any revision surgery afterwards. There was a trend toward shorter time required for intraoperative CT from our earlier to later cases (average 46.5 ± 9.0, range 33 to 70 minutes). In 4 patients, excessive bleeding from the operative fields soiled the drapes during CT scanning procedures. These 4 cases were characterized by older age, more fusion levels, longer total operation time, and higher total amount of blood loss.

Conclusions: By discolosing misplaced screws in a real-time manner, intraoperative CT proved a useful imaging adjunct to MI TLIF. Hemostasis should be secured prior to scanning to prevent unattended bleeding from the operative fields. With experience and coordination, a smooth workflow can be developed in the hybrid OR.

Key words: hybrid operating room, intraoperative computed tomography, minimally invasive transforaminal interbody fusion, percutaneous pedicle screw

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Introduction

Degenerative lumbar diseases (DLDs) are one of the most common causes of low back pain and disabilities,[1] affecting roughly 3.63% of population worldwide.[2] Mild symptoms are axial low back pain and stiffness. As the disease progresses, buttock, thigh, and calf pain and cramping follow. When spinal stenosis is present, intermittent neurogenic claudication develops.[1] If left untreated, the impaired neurological function impacts on a patient's quality of life, general health condition, and even cognitive function.[3,4]

Nonsurgical management for DLD includes pharmacologic interventions, exercise, physical therapy,[5] and epidural steroid injection.[6] While there is evidence that multidisciplinary rehabilitation programs result in improvements of symptom severity, physical function, and walking capacity,[7,8] surgery provides more sustained favorable clinical outcome and enhancement of quality of life.[9] Surgical management involves decompression of nerve roots and thecal sac, with or without fusion.[10] Over the past decades, instrumented fusion has become the mainstream procedure because it provides immediate stability and reduces the risk of pseudoarthrosis.[11,12] Recently, in line with technological advancement, various minimally invasive fusion techniques were developed, and became important surgical options.[13,14] Among them, minimally invasive transforaminal lumbar interbody fusion (MI TLIF) has proved a versatile technique suitable for a wide range of DLD.[15] Compared to open TLIF, MI TLIF offers comparable clinical and radiologic outcomes, but less tissue destruction and blood loss, shorter hospital stay, and faster postoperative recovery.[16,17]

Accurate placement of percutaneous pedicle screws is a critical step in MI TLIF. Misplaced pedicle screws pose risk of implant failure, and injuries to dura, nerve roots, viscera, and major vessels.[18] Different methods have been developed to enhance accuracy of pedicle screw placement, including intraoperative use of navigation systems,[19] cone beam computed tomography (CT),[20] mobile CT,[21] middle pedicle track electromyographic stimulation (t-EMG),[22] and robotic guidance.[23] It has been shown that intraoperative CT yielded high accuracy rates of open spine instrumentation, even in difficult revision cases.[24] However, the use of intraoperative CT in MI TLIF in a hybrid operating room (OR) has not been well addressed. The goals of this study were to report our preliminary experience of performing MI TLIF in the CT hybrid OR of the E-Da Cancer Hospital, and to evaluate the pros and cons of using this supplementary imaging technology in MI TLIF.

Materials and Methods

Patient cohort

From November 2021 to March 2022, 20 consecutive patients with DLD received MI TLIF of the lumbar spine in the hybrid OR. The diseases treated included degenerative lumbar spondylolisthesis, lumbar spinal stenosis, disc degeneration with or without herniation, spondylolytic spondylolisthesis, and degenerative scoliosis. The review of medical records and images was approved by the Institutional Review Board (IRB) of this hospital (EMRP-111-072). All reviewing processes complied with the regulations of the IRB. Patient data are summarized in Table 1.

Surgical procedures

All surgical procedures were performed by the same neurosurgeon (Lu). After general anesthesia and secure establishment of all required tubing, the patient was placed prone on the radiolucent operating table (Maquet Magnus, Getinge, Tokyo, Japan) of the hybrid OR. Pressure relieving viscoelastic pads were

Table 1. Demographic data of patients.

	Number
Patients (female/male)	20 (15/5)
Age	
Range	37 – 84
Mean ± SD*	66.1 ± 11.6
Fusion levels	
One-level	
L3-4	1
L4-5	4
L5-S1	2
Two-level	
L1-2-3	1
L3-4-5	2
L4-5-S1	4
Three-level	
L2-3-4-5	2
L3-4-5-S1	4
Number of implanted screws	
Lumbar	96
Sacral	22
Number of implanted cages	39

* SD: standard deviation.

placed under the chest, pelvic girdle, and knees to prevent pressure sores and create a lordotic curve of the lumbar spine. The steps for MI TLIF were similar to previously published works.[17,25] Briefly, after localization with a mobile C-arm fluoroscopy machine, a paramedian skin incision was made, and the typical Wiltse paraspinal mucle splitting was done with a tubular retractor system with its attached light source (MAST Quadrant Retractor System, Medtronic).[26] Resection of compressive hypertrophic bony and ligamentous structures and discectomy were done microsurgically under an operating microscope (Fig. 1A). Interbody fusion with bone graft and fusion cages, and implantation of percutaneous pedicle screws were performed under continuous C-arm fluoroscopic monitoring (Fig. 1B).

Intraoperative CT scanning

For every patient, after placement of all fusion cages and pedicle screws, the operation was temporarily stopped for intraoperative CT scanning. The wounds were packed with gauze. The patient and operating table were properly draped. The space under the operating table had to be cleared before it was allowed to slide into the CT gantry. Therefore, it was necessary to collect all tubes and catheters connected to the patient, and the wires of all surgical equipment such as electrocautery machines and pneumatic or electric bone drilling systems, and tape them to the covering drapes (Fig. 2A). The Mayo stand and instrument tables were covered and moved away to allow enough room for the operating table to rotate 180 degrees so that the patient's legs were directed toward the CT gantry. When the operating table was unlocked and turned on its base column, the anesthetic

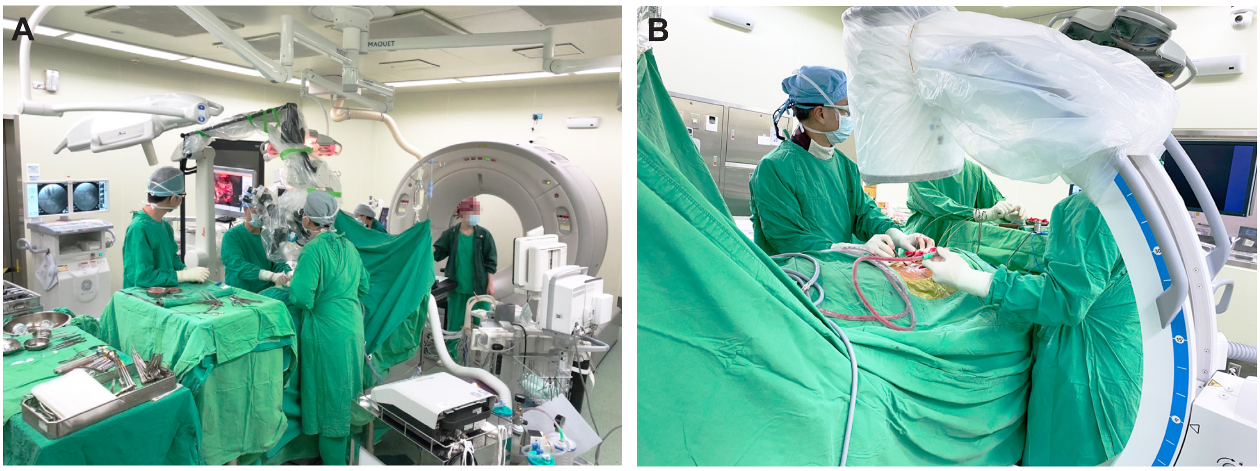

Fig. 1 MI TLIF in a hybrid OR equipped with a CT scanner. Decompressive procedures were performed by using an operating microscope (A), while implantation of pedicle screws and fusion cages under C-arm fluoroscopic monitoring (B).

machine and monitors were moved accordingly. Meanwhile, the patient's endotracheal tube and other connecting catheters were closely watched and protected by the anesthetic team (Fig. 2B). Once the patient was adequately positioned inside the CT gantry (Fig. 2C & 2D), all operating room personnel moved into the CT imaging control room (Fig. 2E). During the imaging process, the patient's vital signs on the monitor panels were viewed through the lead glass shielding of the control room (Fig. 2F).

When the scanning was finished, the images were surveyed immediately by the surgeons in the control room. The trajectory, depth, and position of each pedicle screw and fusion cage, and the integrity of each screwed pedicle, were carefully evaluated. Afterward, the operating table was moved out from the CT gantry, all personnel returned to the operating room to finish the rest of the operation.

Statistical analysis

Comparison between the patients with large blood loss volumes and the others (see Results) was performed with unpaired Student's t-test. All calculations were done by using the Microsoft Excel 365 (Microsoft, Redmond, WA, USA).

Results

CT findings

In the 20 patients, a total of 96 lumbar pedicle screws, 22 sacral alar screws, and 39 fusion cages were implanted. Among the 96 lumbar pedicle screws, 4 screws in 3 patients were found to be too medially positioned (left L4 screw in 2 patients, bilateral L5 screws in 1 patient) (Fig. 3A). The four misplaced lumbar pedicle screws were removed and re-implanted via new entry points and trajectories (Fig. 3B). All the 22 sacral screws were adequately placed. In the 39 disc spaces where bone graft and fusion cages had been implanted for interbody fusion, one fusion cage was found too anteriorly placed with its anterior tip out of the anterior border of the disc space (Fig. 3C & 3D). It was found to be stable in the disc space, and so left alone without further intervention. In another disc space, bone graft penetration through the anterior annulus fibrosus was noted (Table 2).

Time spent for intraoperative CT scanning

The operation time ranged from 180 to 540 minutes, with a mean of 381.9 ± 107.1 minutes. The time required for performing intraoperative CT was defined as the period between the time point when the surgery was interrupted for preparation and that when the operation was resumed after the scanning and image interpretation were finished. The average time spent for CT scanning was 46.5 ± 9.0 minutes, ranging from 33 to 70 minutes.

Extra blood loss during intraoperative CT scanning

After CT scanning, the surgical drapes covering the patients were removed so that the surgery could be resumed. In 16 patients, the covering drapes and operation fields remained clean. In the other 4 cases, blood had overflown out of the wounds and soiled the drapes. The total amounts of intraoperative blood loss in these 4 patients were among the highest in this cohort (1,000 mL, 1,400 mL, 2,300 mL, and 2,700 mL, respectively). Three of them had to be transferred to an intensive care unit (ICU) for postoperative care due to unstable hemodynamic status during the operations.

Two of the four cases underwent 2-level fusion (L4-5-S1), the other two received 3-level fusion (L2-3-4-5, and L3-4-5-S1). A comparison was made between these 4 patients and the other 16 in the cohort. It was found that the 4 patients were older (72.8 ± 12.4 vs. 64.4 ± 2.2, $p = 0.01$). Furthermore, they required longer fusion levels (2.5 ± 0.6 vs. 1.8 ± 0.8, $p = 0.049$), associated with longer operation

Fig. 2 Procedures of intraoperative CT scanning. (A) The patient and operating table were draped with wires taped. (B) The operating table was turned for positioning into the CT gantry while endotracheal tube and vascular catheters under protection. (C) Adjustments were being made on the CT scanner and operating table for positioning. (D) The patient was adequately placed into the CT gantry. (E) Team members had been evacuated, leaving the patient for CT scanning. (F) The patient's vital signs could be viewed through the window of the control room, while scanning and image processing were performed.

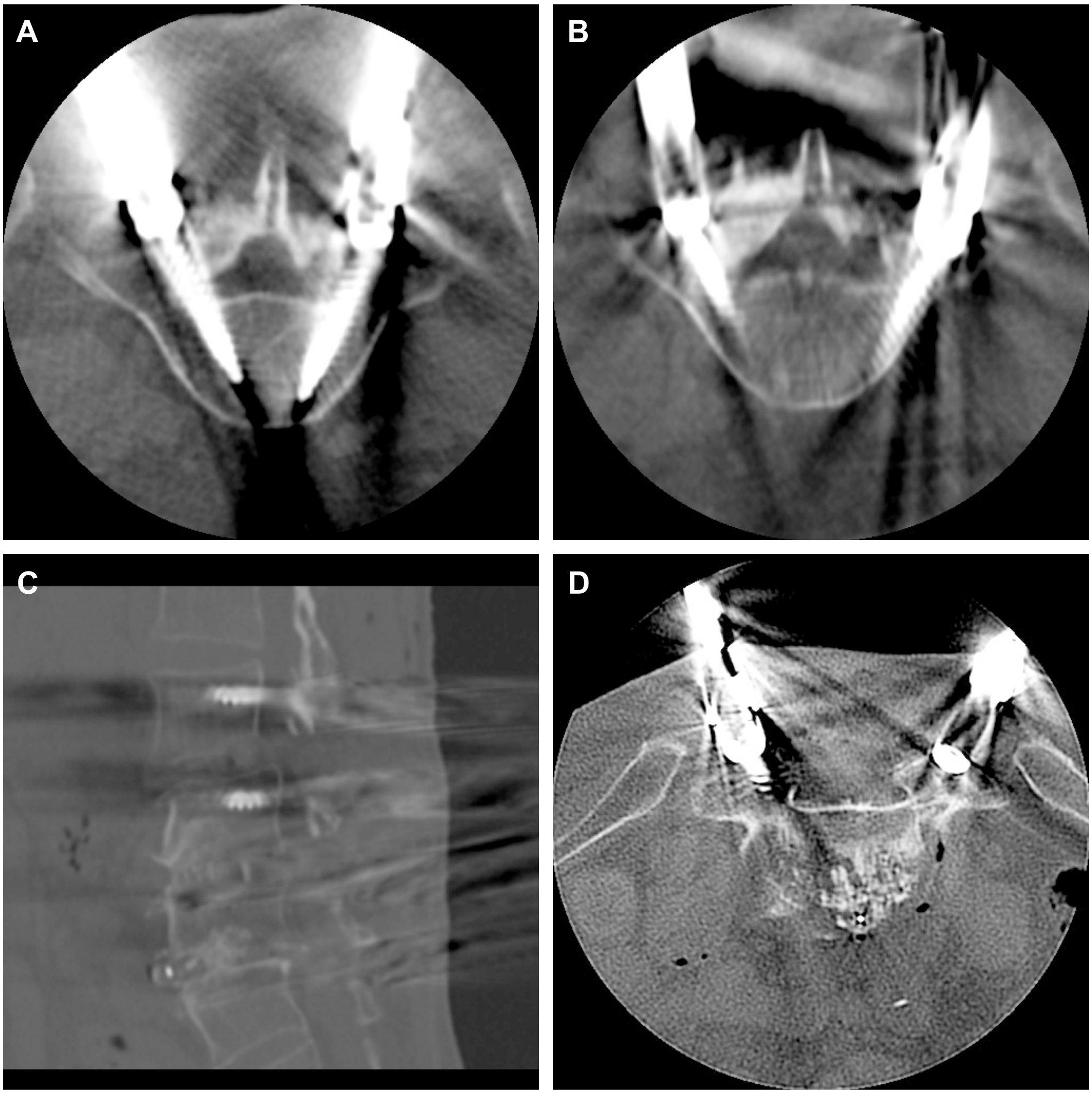

Fig. 3 Intraoperative CT images. (A) Bilateral pedicle screws were too medially placed. (B) Screws were removed and reinserted to adequate positions. (C) and (D) A fusion cage too anteriorly placed in the disc space with its tip beyond the border of the anterior annulus fibrosus.

Table 2. Numbers of adequately placed and misplaced implants shown by intraoperative CT images.

Implants and positions	Number
Lumbar pedicle screws	96
Adequate	92
Too medial	4
Too lateral	0
Completely out of pedicle	0
Sacral screws	22
Adequate	22
Fusion cages	39
Too anterior	1
Too posterior	0
Bone graft	39
Adequate	38
Too anterior*	1

* Penetration of bone graft through anterior annulus fibrosus into retroperitoneal space.

time (465.0 ± 42.0 vs. 361.1 ± 109.0 min, p = 0.01), and higher amounts of total blood loss (1,850.0 ± 785.3 vs. 432.5 ± 406.4 mL, p = 0.03). Although their average T-score was lower than the others, it did not reach statistical significance. The time spent for intraoperative CT scanning was not different from that of the other patients (Table 3).

Clinical outcomes

All the 20 patients had low back pain and radicular symptoms before surgery. After the operations, improvement of radicular pain was observed in all. There was a significant

Table 3. Comparison between patients showing blood-soaked drapes (n = 4) and those showing clean drapes (n = 16) after CT scanning.

	Bloody drapes	Clean drapes	*p* value*
Patient number	4	16	
Age (mean ± SD)	72.8 ± 12.4	64.4 ± 2.2	0.01
Fusion levels	2.5 ± 0.6	1.8 ± 0.8	0.049
Operation time (min)	465.0 ± 42.0	361.1 ± 109.0	0.01
CT scanning time (min)	46.8 ± 8.5	45.7 ± 7.6	0.85
Total blood loss (mean ± SD) (mL)	1,850.0 ± 785.3	432.5 ± 406.4	0.03
T-score	−2.5 ± 0.5	−2.1 ± 1.8	0.48

* Statistical analysis was performed using unpaired Student's t test.
SD: standard deviation.

drop of pain visual analogue scale (VAS) from preoperative (mean 7.05 ± 2.19, range 2 to 10) to final follow-ups (mean 1.85 ± 1.76, range 0 to 6) ($p < 0.00001$). Seven patients had mild low back soreness, and 5 had moderate back pain requiring medications. Four patients felt numbness on one or two legs, while one complained of burning sensation on the thighs. All the symptoms were temporarily and gradually improved on subsequent follow-ups. No patient had new radicular symptoms caused by misplaced pedicle screws, and none needed a revision surgery. Preoperative neurogenic claudication was present in 14 patients. Their ability to walk all improved, although 5 of them still needed a walker on the last follow-up visits.

Discussion

Accurate percutaneous pedicle screw placement is of utmost importance in lumbar fusion surgery. Although the reported incidence of misplaced pedicle screws in MI TLIF is relatively low (1.1 to 1.4%),[17] this complication may cause dural tears and nerve root irritation or injury, resulting in postoperative radicular pain and neurological deficits.[27,28] According to a recent study, misplacement of pedicle screws is the most common cause of malpractice litigations on spine surgery in the United States.[29]

Currently, our method for intraoperative localization of pedicles is C-arm fluoroscopy-based. With this imaging modality of two-dimensional visualization of the spine, it is sometimes difficult to accurately place a pedicle screw without breaching the pedicle walls, especially in obese patients or those with suboptimal image quality. In this series, even though all percutaneous pedicle screws and fusion cages were implanted under constant alternating anterior and lateral C-arm fluoroscopic monitoring, 4 of 118 screws (96 lumbar and 22 sacral) were found to be too medially placed. If not for the intraoperative CT scanning, these misplaced pedicle screws would have remained undetected, and most likely would cause postoperative complications, which would require revision surgery for correction. The fact that none of our patients suffered new postoperative radicular symptoms and needed a revision operation is a strong evidence supporting the benefit of intraoperative CT scanning provided by the hybrid OR.

Extra time and resources for intraoperative CT scanning

Obviously, intraoperative CT scanning in a hybrid OR requires a complex workflow. Communication and coordination between surgical, anesthetic, nursing, and radiology teams are key factor for a smooth and uneventful operation. Logistic support from the hospital is also important because intraoperative CT scanning requires prolonged OR occupancy, personnel working hours, and additional surgical materials, all of which are valuable resources of a hospital from an administrative point of view.

In the first few cases of this cohort, it took an hour or more for intraoperative CT scanning. However, as all the OR and radiology personnel gradually became familiar with the preparatory processes, the time was reduced to as short as 40 minutes. This implies that a standardized workflow and cooperation between different members in the OR can potentially shorten the time needed for intraoperative CT scanning and image interpretation.

Potential risk of increased intraoperative blood loss

In four patients, blood-soaked drapes were noted when the coverings were removed after intraoperative CT scanning. This indicates that in these patients bleeding from the operative fields continued while the CT scanning was performed and images were read. Although routinely all wounds were packed with gauze down to the subfascial spaces before the CT scanning procedures, the skin incisions remained open. This might have significantly reduced the tamponade effect due to the lack of a closed compartment. Once the amounts of blood in the wounds exceeded what the packing gauze could contain, blood overflew over the brims of the wounds without limit.

Since increased blood loss may adversely affect a patient's outcome, it is important for surgeons to be able to control bleeding from the operative field when they have to be away from the patient during the intraoperative CT scanning. Currently, the methods used for hemostasis in our MI TLIF surgery include waxing for bone bleeding, Surgicel and cottonoid patties packing, and electrocoagulation for soft tissue and epidural venous bleeding. Apparently, in these 4 patients, packing inside the wounds failed to effectively stop ongoing bleeding. As shown in Table 3, these patients were characterized by older age, longer fusion levels, longer total operation time, and significantly greater total blood loss amounts (Table 3). These findings suggest that for such patients, more proactive measures should be considered preoperatively, including preparation for more aggressive fluid resuscitation, blood transfusion, booking of an ICU bed, and intraoperative administration of tranexamic acid, or use of hemostatic agents such as Floseal gelantin-thrombin matrix sealant or other related products. Further studies with more subjects are warranted to clarify the risk factors contributing to higher amounts of intraoperative blood loss, and effective methods to tackle this potentially harmful situation while performing intraoperative CT scanning in MI TLIF surgery.

Limitations

There are several limitations to this study. This is a retrospective analysis of a limited number of patients with short follow-up periods. Although the patients reported symptom relief and showed improved ability to ambulate following the operations, it is not clear, from the findings of our study, how much intraoperative CT scanning contributed to the favorable surgical outcomes. Further prospective studies are necessary to clarify the differences between MI TLIF with or without intraoperative CT guidance. Lastly, it is to be noticed that there remains room for improvement in the intraoperative CT workflow, and that our preliminary experience should be viewed as justification for continued coordinated team work in the hybrid OR.

Conclusions

Our experience shows that performing MI TLIF surgery in a CT hybrid room is feasible and rewarding, given the high-quality imaging complement provided by the CT scanning. Even though the CT scanning requires extra time, and may increase intraoperative blood loss in MI TLIF, it effectively detects implant errors in real time, and eliminates the need for revision surgery to correct misplaced pedicle screws or fusion cages. Quality communication and coordination between surgeons and members of different departments in the hybrid OR are essential for a smooth workflow that could potentially reduce the time required for intraoperative CT scanning.

Author Contributions

Stdudy Design, Kang Lu, Chih-Lung Hung, Chao-Ming Hung; Data Collection, Kang Lu, Chun-Chung Lui; Statistical Analysis, Chong-Chi Chiu; Data Interpretation, Kang Lu, Chong-Chi Chiu; Manuscript Preparation, Kang Lu; Literature Search, Kang Lu, Chun-Chung Lui.

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Institutional Review Board Statement

The study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board (IRB) of the E-Da Hospital (EMRP-111-072).

Informed Consent Statement

Patient consent was waived due to the nature of the study being a retrospective analysis, of which all private patient-related information were strictly protected and anonymized throughout preparation and submission of the manuscript. None of the written content or figures contains any identifiable information of subjects involved in the study.

Data Availability Statement

Derived data supporting the findings of this study are available from the corresponding author (Kang Lu) on request.

Conflicts of Interest

The authors declare no conflict of interest.

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