Technical Note

Indocyanine Green Fluorescence-Guided Knee Arthroscopy: A Technical Note for Investigating the Microvasculature Around the Meniscus

Tamiko Kamimura, M.D., Ph.D.

Abstract: Vascularity of the meniscus is the most important key to meniscal tear healing. However, blood supply to the meniscus is limited to approximately the outer 10% to 25% of the meniscus, known as the "red-red zone." The cyanine dye indocyanine green (ICG) is commonly used as a contrast imaging agent for visualizing vascularity in several medical fields. Moreover, ICG fluorescence-guided surgery is a modern trend in the field of laparoscopic surgery in which the characteristic of fluorescence enhancement under a near-infrared light is used. However, ICG fluorescence-guided knee arthroscopy findings remain unknown. In this Technical Note, the author applied ICG fluorescence-guided surgery to knee arthroscopy to evaluate blood supply to the meniscus and intra-articular apparatus. Additionally, the arthroscopic findings of ICG fluorescence-guided knee arthroscopy for degenerative tears of the medial meniscus before and after meniscal repair are presented. Through the intravenous injection of ICG solution, real-time detection of fluorescence may contribute to investigating case-specific vascularization of the meniscus during arthroscopy in the next generation.

The role of meniscal vascularity in healing meniscal tears is crucial. However, meniscal vascularization is limited to what is known as the "red-red zone": the outer 10% to 25% of the meniscus.[1] The cyanine dye indocyanine green (ICG) is commonly used as a contrast imaging agent for visualizing vascularity in clinical hepatology and angiocardiology. It is increasingly used for laparoscopy owing to its characteristic of fluorescence enhancement under a near-infrared light with a wavelength of approximately 750 to 810 nm.[2,3]

In 2018, the author started to apply a laparoscopic ICG procedure to investigate the basic vascularity of knee structures and real-time vascularization. However, there is major difficulty in evaluating the knee joint structures using this procedure: The standard laparoscope (5.4 mm in diameter) is too long to observe the broad condition in perspective. Owing to recent improvements in imaging, a 4.0-mm arthroscope for a 4K camera system can be used with the ICG fluorescence-guided protocol, with laparoscopic settings not entirely needed, enabling a more easy application to arthroscopy for clinical use.

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Surgical Technique

Patient Positioning

The patient is placed in the supine position on the table edge to the extent possible and alternatively using a lateral post for primary purposes as in standard arthroscopic surgical procedures.

Preparation of ICG Solution for Intravenous Injection

ICG (Diagnogreen for Injection, 25 mg; Daiichi Sankyo, Tokyo, Japan) is dissolved in 10 mL of sterile water, yielding ICG solution (2.5 mg/mL) for injection (Fig 1). Intravenous injections of 2.0 mL of ICG solution are followed by injection of an equal quantity of saline solution.

Surgical Equipment and Modalities for Observation

The author uses an arthroscope combined with a 1688 Advanced Imaging Modalities (AIM) 4K Platform camera system and L11 light source (Stryker, Kalamazoo, MI). Fluorescence-guided arthroscopy is used for the observation of 3 modality patterns: standard

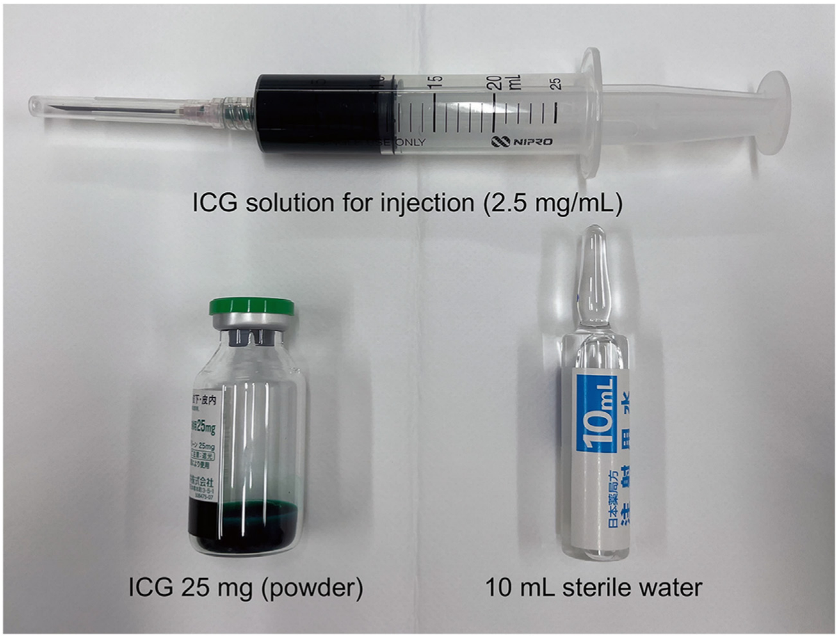

Fig 1. Preparation of indocyanine green (ICG) solution. ICG (25 mg) is dissolved in 10 mL of sterile water, yielding ICG solution (2.5 mg/mL) for injection.

arthroscopy, SPY overlay, and SPY contrast. SPY overlay is the color mode, and ICG fluorescence is observed as bright green in the standard arthroscopy mode. SPY contrast is the black-and-white (dark monochrome) mode, which is the optimal mode for assessing vascularization (Video 1).

ICG Fluorescence-Guided Knee Arthroscopy

Step 1: Basic Observation Using ICG Fluorescence-Guided Arthroscopy. In this technique protocol, the standard arthroscopy mode setting is prepared, the camera is set in ICG mode, and the operating room lights are turned off to clearly observe fluorescence. A tourniquet is not used. Additionally, the flow pump pressure is adjusted to 40 mm Hg with a flow rate of 0.3 L/min to maintain the natural state of blood circulation of the affected lower extremity as much as possible. An irrigation trocar or needle cannula is used for fluid outflow to ensure a clear arthroscopic view during surgery. After conventional diagnostic arthroscopy, a single-bolus intravenous injection of 2.0 mL of ICG solution (2.5 mg/mL) is administered. Time counting is then performed, starting at the time of injection and ending when fluorescence is observed to be completely attenuated within the joint. The times of fluorescence onset and attenuation are recorded. Observation starts from the lateral compartment according to the author's observational protocol of ICG fluorescence-guided arthroscopy. Fluorescence is observed at the synovium

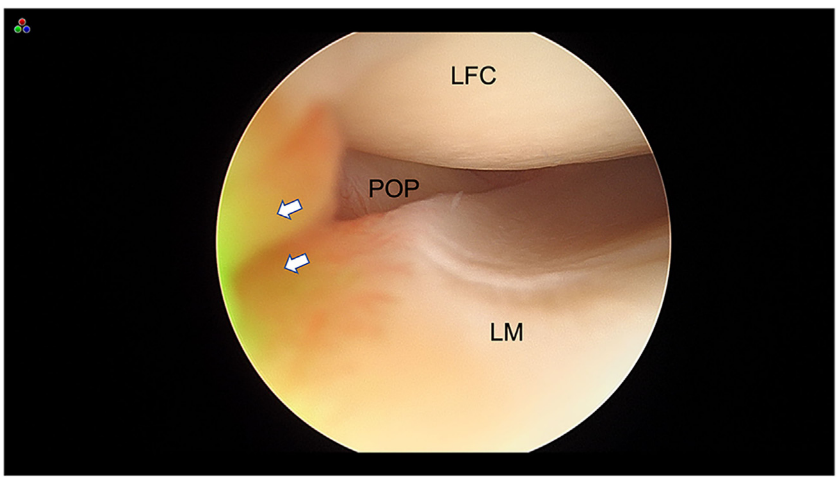

Fig 2. Observation of lateral compartment in right knee. The observational protocol of indocyanine green fluorescence-guided knee arthroscopy starts from the lateral compartment. Fluorescence is observed at the synovium around the popliteus tendon (POP) (arrows). (LFC, lateral femoral condyle; LM, lateral meniscus.)

around the popliteus tendon (Fig 2). However, no fluorescence is observed at the body of the meniscus within the white zones with administered ICG solution before procedures (meniscal repair in the present case) (Fig 3A).

At the adjacent synovium of the meniscus, fluorescence is observed. Moreover, the anterior cruciate ligament is partially brighter (Fig 3B). However, the medial meniscus and its surrounding synovium are often observed to be less fluorescent than the lateral meniscus. After the synovium undergoes a stimulation procedure, such as rasping, fluorescence is not observed at the synovium or the meniscus within a short waiting period (Fig 3C).

On the basis of the author's experience, approximately 20 to 40 seconds after injection, fluorescence is observed as excitation within the synovium, gradually spreading to the surrounding area, and lasts for approximately 15 minutes before the attenuation phase. Owing to the limited duration of fluorescence, efficient observation is required. Because there are individual differences in the onset time and duration of fluorescence emission, the waiting period is not constant. These procedures are presented in Table 1, whereas pearls and pitfalls are listed in Table 2.

Step 2: Surgical Step (Required Procedures in Each Case). In the case in this Technical Note, meniscal repair is performed. The degenerative flap of the medial meniscus is then reduced, after which debridement is performed. Meniscal repair is performed using the inside-out technique with fibrin clot augmentation.

Step 3: Repeated Observation With ICG Administration After Procedures (Meniscal Repair). After completion of the procedures in each case (meniscal repair in this Technical Note), a repeated ICG solution injection is performed once to evaluate the findings before and after the procedure. After repair of the complex tear, fluorescence is not clear at the repaired tear site (Fig 3D). However, fluorescence at the synovium of the meniscocapsular junction, along with the area undergoing stimulating procedures such as rasping and/or meniscal repair, is brighter than before repair (Fig 4A).

Several minutes after ICG solution administration, fluorescence spreads widely with further brightness (Fig 4B). The emitted fluorescence is particularly dense at the rasping and adjacent sutured sites in the presented case (Fig 4, Video 1).

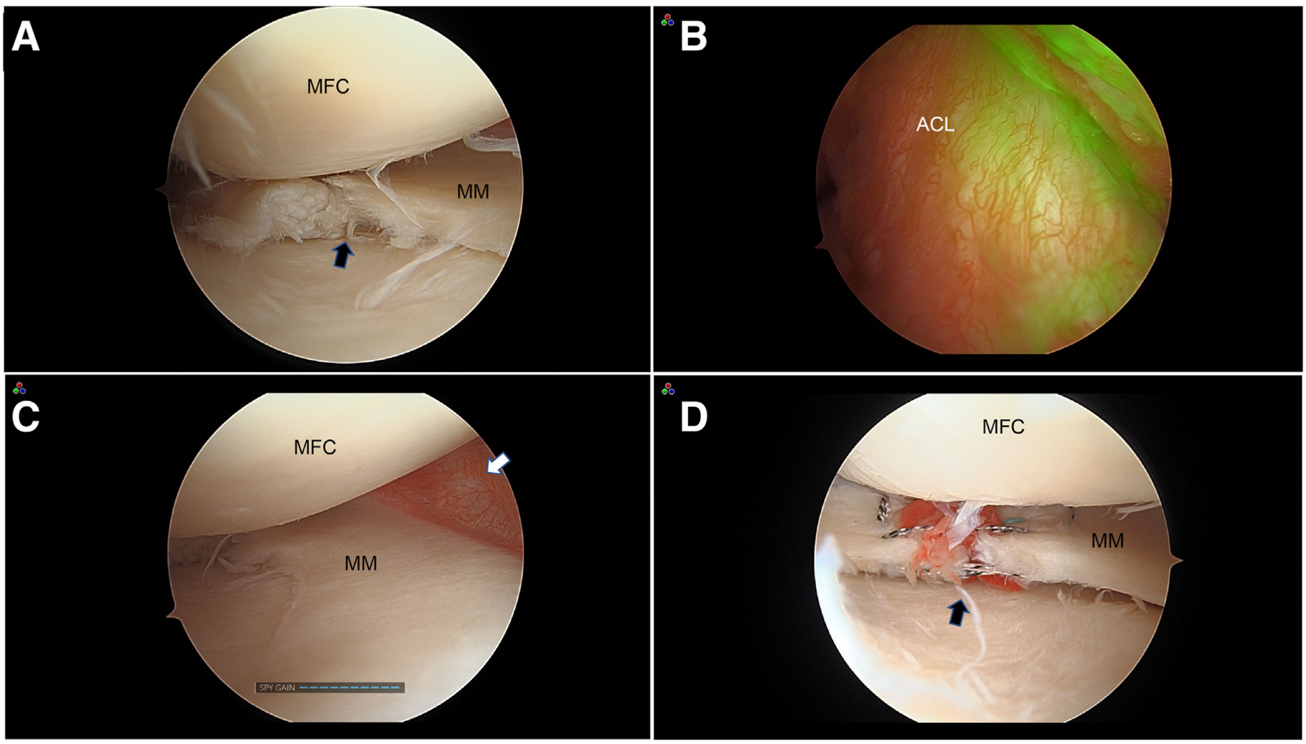

Fig 3. Observation of medial compartment and anterior cruciate ligament (ACL) with degenerative complex radial tear of medial meniscus (MM) in right knee. (A) A degenerative radial tear of the MM is revealed. However, no fluorescence is observed before the repair (black arrow). (B) The anterior synovium of the ACL fluoresces in bright green in SPY overlay mode. (C) Rasping is performed. However, fluorescence is not observed before meniscal repair (white arrow). (D) A repeated indocyanine green solution injection is performed to evaluate the findings before and after meniscal repair around the repaired site. Meniscal repair is performed using the inside-out technique with fibrin clot augmentation. However, no fluorescence is observed at the repaired site (black arrow). (MFC, medial femoral condyle.)

Table 1. Observation Steps for ICG Fluorescence-Guided Knee Arthroscopy

- A standard diagnostic arthroscopy setting is prepared.
- The camera system is set in ICG mode.
- The lights in the operating room are turned off.
- A single-bolus intravenous injection of 2.0 mL of ICG (2.5 mg/mL) is administered.
- Fluorescence is observed with time counting.

ICG, indocyanine green.

Table 2. Pearls and Pitfalls

Pearls
- A tourniquet is not used for maintaining blood circulation in the affected lower extremity.
- The flow pump pressure is adjusted as naturally as possible (40 mm Hg with a flow rate of 0.3 L/min).
- An irrigation trocar or needle cannula should be used for fluid outflow to ensure a clear arthroscopic view.
- There should be a waiting period for fluorescence emission with time counting from ICG injection as a reference for the repeated observation after the procedure.

Pitfalls
- The limited duration of fluorescence requires efficient observation until attenuation.
- Because there are individual differences in the onset time of fluorescence emission, the waiting period is not constant.

ICG, indocyanine green.

Discussion

In 1982, Arnoczky and Warren[1] observed limited vascularity of the human meniscus, noting the small amount of blood supply received by the bilateral menisci from the terminal branches of the bilateral genicular arteries in cadaveric specimens. Moreover, Day et al.[4] and Cooper et al.[5] showed that vascular penetration of the meniscus was limited to the peripheral one-third, classifying the zones of meniscal vascularity as indicators of meniscal repair in 1985 and 1990, respectively. Because these studies indicated the segmental classifications of red-red, red-white, and white-white zones, they provided the foundation for standard surgical planning of meniscal repair. However, it remains difficult to predict the prognosis of meniscal repair with only the segmental classification of the injured area owing to multiple factors that can affect the results of repair, such as age.[6,7] Additionally, Michel et al.[8] investigated the age and microvasculature of the human meniscus, including zone specificity and the capsule, concluding that vessel formation was not detected within the red-white and white-white zones and its tendency increases with age. However, the capsule was more densely vascularized than the meniscus. Chahla et al.[9] found larger vessels in the red-red and red-white zones and showed the presence of small vessel tissues and endothelial cells in the white-white zone using immunofluorescence in cadaveric specimens from young healthy adults. This finding might indicate that tears in this region could have more healing potential than previously thought. These recent studies and the advancement in surgical technology have enabled surgeons to preserve the meniscus positively, even in older patients.[10,11]

Factors such as joint instability (anterior cruciate ligament deficiency), subchondral edema, and degenerative changes within the complex dynamics of the knee joint could also affect surgical outcomes.[7,11] Additionally, individual patient lifestyle habits such as smoking and alcohol use may be considered at the time of surgery.

Given these individualized intra-articular environments, visualizing the vascularity of the meniscus and adjacent synovium in each case—as there have been some cases of failure even with consistent surgeon effort—is necessary. Thus, if surgeons could visualize the vascularity of the meniscus at the time of arthroscopic meniscal surgery, this may be used for predicting the prognosis in each case. This technique aims to

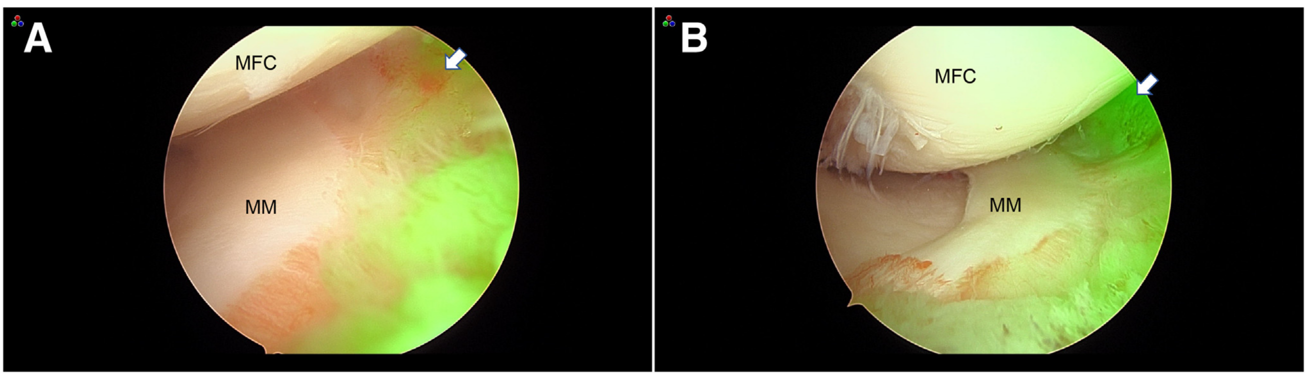

Fig 4. Additional waiting period after repeated indocyanine green solution injection after meniscal repair of medial meniscus (MM). (A) Fluorescence is gradually diffused over a wide range at the synovium of the MM. However, the rasping site is not fluorescent (arrow). (B) After a waiting period of approximately 12 minutes, extensive fluorescence is observed; it is brighter and concentrated after repair, particularly in the rasped region (arrow). (MFC, medial femoral condyle.)

Table 3. Advantages and Disadvantages

Advantages (Benefits)
• The technique provides real-time detection of vascularization within a target structure using fluorescence imaging during arthroscopy.
• Case-specific vascularity of the knee joint structures may be evaluated.
Disadvantages (Risks)
• Cases with contrast media allergy are contraindicated.
• The technique requires an ICG-compatible camera system with a NIR light source.
• Because of case-specific factors, a waiting period is required from ICG injection to fluorescence detection.
• The standard characteristics of ICG arthroscopic findings are unknown at present.

ICG, indocyanine green; NIR, near-infrared.

investigate a "case-specific" predictable procedure for determining the healing potential of meniscal tears.

In 2009, Ishizawa et al.[12] first reported ICG fluorescence-guided cholecystectomy and gave increased attention to an optical imaging guidance procedure using endoscopy with a near-infrared light source for accurately evaluating the target organ.[2,3,12] Nevertheless, studies of ICG in the orthopaedic field are currently limited. Doi et al.[13] described the vascularity of soft tissue using an ICG solution for shoulder arthroscopy. Moreover, van Schie et al.[14] assessed the vascularity of the anterior horn of the meniscus in a total knee arthroplasty case. Sepehri et al.[15] used the SPY fluorescence imaging system for performing laser-assisted ICG angiography to assess soft-tissue perfusion in tibial fracture cases. However, ICG fluorescence-guided knee arthroscopy has not yet been reported.

By use of ICG fluorescence-guided knee arthroscopy, brighter fluorescence is emitted around the stimulated area with rasping, requiring a waiting period from synovial stimulation to fluorescence detection. This may be one of the key findings of the activation of the circulation of synovial coverage, which might contribute to meniscal healing.

However, the relation between localized brightness of fluorescence and blood supply to the meniscus, along with how to interpret the degree of bright fluorescence intensity, remains unknown. The author suggests that the hemodynamics of the meniscus remain unrevealed, and there is some possibility that the conspicuous blood vessels do not always circulate vigorously; sometimes they are congested and/or retarded by weight bearing within the knee joint as previously reported in studies on the anatomy of the age-related changes of the meniscus.[6,8,10,16]

Currently, it remains difficult to interpret the significance of fluorescence as the evaluation of meniscal circulation. Furthermore, standardization of the arthroscopic protocol based on the characteristics of ICG arthroscopic findings is necessary. Future studies are required to establish the criteria for arthroscopic visualization.

The greatest advantage of ICG fluorescence-guided arthroscopy is that it enables real-time evaluation of the vascularity of the knee structures, including the meniscus, in a living human, which until now has been limited to cadaveric experiments. However, this technique requires intravenous injection of ICG as a contrast agent and is not suitable in patients with a history of allergy to iodine contrast media. The advantages and disadvantages of this technique are listed in Table 3. The author suggests that ICG fluorescence-guided arthroscopy could serve to elucidate the case-specific factors of vascularization and perfusion of the meniscus as bio-optical navigation surgery in the next generation.

Disclosures

The author declares no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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