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The Anatomical Basis and Clinical Progress of Pericapsular Nerve Block Technique for Hip Joint

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Abstract:Objective: To systematically review the anatomical basis, clinical application effects, and research progress of pericapsular nerve group (PENG) block technique, providing reference for clinical analgesia plan selection. **Methods:** Relevant literature at home and abroad was searched, summarizing the anatomical characteristics and technical innovations of PENG block, comparing the limitations of traditional block techniques, analyzing its clinical analgesic effects, preservation of motor function, and safety, summarizing current controversies and looking forward to future directions. **Results:** PENG block is based on the multi-source nerve distribution (femoral nerve, obturator nerve, and accessory obturator nerve supply) and the separation characteristics of sensory-motor nerve pathways at the anterior capsule of the hip joint. Through ultrasound-guided targeted injection (with the puncture needle inclined at 30-45° to the midpoint of the line connecting the anterior inferior iliac spine and the pubic tubercle), sensory-motor separation block can be achieved. Clinical studies show that PENG block can reduce dynamic visual analog pain scores (Visual Analogue Scale, VAS) in patients with hip fractures (from 7.8 to 3.2), reduce morphine consumption by 45% in patients undergoing total hip arthroplasty (Total Hip Arthroplasty, THA) within 12 hours postoperatively, and achieve a quadriceps muscle strength retention rate of 92% at 6 hours post-THA, with a major complication rate of only 1.4%. Current controversies focus on differences in access methods (direct vision vs. ultrasound guidance) and drug parameters (optimizing local anesthetic concentration at 18-20mL), with long-term safety data still needing to be supplemented. **Conclusion:** PENG block has achieved precision in hip joint analgesia, highly aligning with the concept of enhanced recovery after surgery (Enhanced Recovery After Surgery, ERAS), and is a high-quality alternative to traditional block techniques. Future improvements in clinical value should be made through artificial intelligence-assisted positioning and multimodal analgesia integration.

Keywords: Hip joint pericapsular nerve block; Anatomical basis; Clinical application; Analgesia; Enhanced recovery after surgery.

Hip joint pain is a common and intractable problem in clinical practice, and it is more significant in patients with hip fractures and those undergoing hip joint surgery [1]. Research shows that even slight movement before surgery can cause severe pain in patients with hip fractures, seriously reducing their quality of life [2]; Patients who have undergone hip replacement often suffer from severe pain in the early postoperative period and need to use high-dose opioid drugs for pain relief. However, the side effects can also delay the quality of postoperative recovery [3]. Traditional pain relief methods are difficult to effectively solve the problem of dynamic pain (such as pain during activity). Clinically, there is an urgent need for a new type of pain relief plan that can take into account both analgesic effects and retain motor function [4]. The ultrasound-guided nerve block technique has become one of the commonly used methods for multimodal analgesia in hip joint surgeries. Among them, femoral nerve block (FNB) has a good analgesic effect, but it can cause a decrease in the strength of the quadriceps femoris muscle, which affects the postoperative activities and rehabilitation of patients [5]

The analgesic effect of fascia iliaca compartment block (FICB) is unstable and the impact on motor function is still unclear [6]. The traditional blocking techniques cannot achieve selective blocking of sensory and motor nerves, so there is an urgent need for more precise targeted blocking approaches in clinical practice [7]. Many studies have begun to focus on specific nerve block schemes for the hip joint capsule to optimize the postoperative analgesic effect [8].

With the widespread adoption of the Enhanced Recovery After Surgery (ERAS) concept and the day surgery model, regional block techniques that can ensure effective intraoperative analgesia while preserving patients' motor functions and promoting rapid postoperative recovery have become increasingly important [9]. Against this backdrop, the periprosthetic nerve block (PENG) technique for the hip joint emerged.This technology can specifically block the joint branches of the main sensory nerves (femoral nerve) and main motor nerves (obturator nerve) that innervate the flexor muscles of the lower limbs, achieving the separation and blockage of the sensory and motor nerves in the anterior compartment of the hip joint [10]. Clinical applications have shown that PENG block not only effectively controls the dynamic pain of patients with hip fractures [2], but also provides excellent postoperative analgesic effects for patients undergoing hip arthroscopy and hip replacement surgery [5,11]. Its most significant innovation lies in designing a precise puncture route based on the three-dimensional anatomical characteristics of the nerve innervation of the hip joint capsule, thereby increasing the probability of local anesthetic reaching the target nerve [12], and promoting hip joint pain management into the era of

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precision and individualization [8].

1 The anatomical basis of nerve innervation of the hip joint capsule

1.1 The nerve distribution characteristics of the anterior joint capsule

The anterior capsule of the hip joint is mainly innervated by the femoral nerve, the obturator nerve and their branches, and is innervated by multiple sources. The afferent receptors of the femoral nerve are distributed in the anterior part of the hip joint capsule [2]; the obturator nerve innervates the anterior medial part of the joint capsule [13], and approximately 30% of individuals have an accessory obturator nerve in the anterior inferior capsule region [15]. Autopsy studies have revealed that the joint branches of the femoral nerve and the branches of the obturator nerve together form the reticular neural tissue of the anterior joint capsule. The anterior lateral part is mainly composed of the joint branches of the femoral nerve, which are the most numerous, while the anterior medial nerve branches mainly originate from the obturator nerve [14]. This segmental nerve distribution pattern provides an anatomical basis for the localization of target nerve block.

1.2 The differences in the course of sensory nerves and motor nerves around the joints

The peripheral nerves around the hip joint are separated into sensory nerve fibers and motor nerve fibers. The sensory branch of the femoral nerve located at the level of the iliac and lumbar muscles runs beneath the lateral tendon membrane of the iliac and lumbar muscles and terminates at the nociceptive receptors in front of the joint capsule [6]. The motor fibers then descend and enter the quadriceps femoris muscle [11]. The anterior branch of the obturator nerve is contained within the obturator canal and includes both sensory fibers that innervate the joint capsule and motor fibers that innervate the adductor muscles [3]. Anatomical studies have confirmed that this functional separation creates conditions for selective blockage of the sensory nerves of the joint capsule while preserving the motor function [8]. Additionally, the accessory obturator nerve, as a variant of the obturator nerve, has an independent nerve plexus and is distributed at the lowest part of the anterior joint capsule and innervates the pubococcygeus muscle [15].

1.3 The significance of three-dimensional anatomical positioning in guiding block techniques

The three-dimensional distribution characteristics of the nerve innervation of the hip joint capsule determine the positioning method of the block technique. Imaging studies have shown that the joint branches of the femoral nerve form a dense nerve plexus 1-2 cm anterior to the connection line between the iliac anterior inferior spine and the iliac pubic 隆起 [14], which is the key target of PENG block [16]. Ultrasound anatomical studies have confirmed that the injected local anesthetic can effectively spread to the iliac psoas muscle plane without reaching the pubic inferior plane where the motor branches of the obturator nerve are located [12]. Autopsy studies further demonstrated that for successful block, the diffusion range of the local anesthetic must simultaneously cover the anterior end of the iliac psoas muscle plane and the pubic inferior space [17], enabling the drug diffusion range to match the nerve innervation range of the joint capsule, thereby ensuring the block effect [16].

2 Traditional Hip Joint Nerve Block Techniques

2.1 The targeted nerves and limitations of the iliac fascia compartment block (SFICB)

The iliac fascia space block (FICB) targets the femoral nerve and the lateral femoral cutaneous nerve as the anesthetic nerves. It achieves analgesic effects by injecting local anesthetic into the potential anatomical space between the iliac fascia and the iliac muscle [18]. It was widely used in hip joint surgeries, but it had significant limitations: on one hand, it could not block the branches of the obturator nerve, making it difficult to cover the nerve innervation of the anterior capsule of the hip joint, and the analgesic effect was limited; on the other hand, it would block most of the motor branches of the femoral nerve, resulting in about 70% of patients experiencing reduced quadriceps muscle strength, which affected early postoperative activities [16]. Clinical studies have shown that the modified supra-iliac fascia approach block (SFICB) can improve the diffusion range of local anesthetic towards the lumbar plexus, but it still fails to solve the problem of motor blockage [19].

2.2 The effect of femoral nerve block (FNB) on motor function

Femoral nerve block (FNB) achieves precise analgesic effects by directly blocking the main trunk of the femoral nerve, resulting in a significant reduction in the dosage of opioid drugs used by patients within 24 hours after surgery [20]. However, FNB causes considerable damage to motor function, with 80% of patients experiencing limited knee extension during and after the operation, delaying postoperative activities and prolonging hospital stay; even with the use of low-concentration local anesthetics (0.25% bupivacaine), the quadriceps muscle strength of patients 6 hours after FNB was still weaker than that in the PENG block group [16]. This obvious motor block effect limits the application of FNB in the ERAS (Enhanced Recovery After Surgery) protocol [22].

2.3 The technical combination of multi-neural combined block

To overcome the limitations of single nerve block, clinicians often adopt a multi-nerve combined block protocol. The FRONT block uses a double-injection method to block the femoral nerve and the main trunk of the obturator nerve, which can achieve extensive block of the anterior capsule of the hip joint. However, this operation significantly increases the difficulty [16]. Additionally, there are cases where the iliac fascia block is combined with the sciatic nerve block to enhance the analgesic effect of the posterior capsule of the hip joint, but this will increase the total amount of local anesthetic, prolong the operation time, and inevitably lead to combined motor nerve block [14].

3 PENG hinders technological development

3.1 Targeted nerve selection strategy under ultrasound guidance

The key technological innovation of PENG block lies in the precise identification of sensory nerve branches surrounding

the hip joint capsule through ultrasound. By placing the ultrasound probe between the anterior inferior iliac spine (AIIS) and the ilio-pubic eminence (IPE), the nerve distribution in the front of the hip joint capsule can be clearly displayed [24]. The injection target is the nerve branch that supplies approximately 90% of the sensory fibers of the anterior side of the hip joint. Compared with blind puncture, ultrasound can ensure that the local anesthetic is precisely deposited in the potential anatomical gap between the joint capsule and the latissimus dorsi tendon [25]. Relevant reports show that the success rate of PENG block under ultrasound guidance is as high as 92%, significantly higher than the block method relying on surface anatomical positioning [26].

3.2 The anatomical basis for the path of the puncture and the diffusion of the drug solution

The puncture path of PENG block is based on the three-dimensional neuroanatomical characteristics of the hip joint capsule. The puncture needle is inserted at a downward inclination of 30-45 degrees towards the inner side of the ilium, with the needle tip located at the midpoint of the line connecting the anterior inferior iliac spine and the ilio-pubic 隆起 [24]. Autopsy studies have shown that 18-20 mL of local anesthetic can fully cover the joint branches of the femoral nerve and the accessory obturator nerve, spreading along the fascial plane between the latissimus dorsi muscle tendon and the ilio-pubic 隆起， forming a "tear-drop" distribution range [14,25]. The key to the operation is that the local anesthetic should not spread to the medial area where the main trunk of the femoral nerve is located, in order to preserve motor function [24]. Clinical observations have found that when using 20 mL of 0.5% ropivacaine, the local anesthetic can cover 83% of the target innervated nerve area, and does not affect the patient's autonomous activity ability [5,27].

3.3 Feeling - The Mechanism of Separation Block in Motor Function

PENG achieves sensory-motor dissociation block by selectively targeting the sensory nerve branches of the joint capsule. An anatomical study has confirmed that the femoral nerve, after sending out the motor branches that control the quadriceps femoris, branches out into fine sensory branches that are distributed on the anterior side of the hip joint capsule [14,25]. Therefore, when local anesthetic is applied to the distribution area of the sensory branches of the joint, it can effectively provide pain relief while preserving the muscle strength of the quadriceps femoris [7]. Clinical muscle strength tests have shown that compared with conventional femoral nerve block, the muscle strength score of the quadriceps femoris in patients with PENG block is higher (6 hours after surgery: 4.2 ± 0.8 vs 1.5 ± 0.7) [7], and is more suitable for patients undergoing hip joint surgery who need to get out of bed early [16,22]. However, it should be noted that approximately 5% of cases may experience temporary muscle weakness due to accidental diffusion of the drug solution to the femoral nerve trunk [12].

4 Clinical application effect study

4.1 Assessment of analgesic effect: VAS score and opioid dosage

Multiple randomized controlled trials have confirmed that PENG block can provide excellent analgesic effects for patients undergoing hip joint surgery. For patients undergoing hip arthroscopy, the visual analogue scale (VAS) pain score at rest 24 hours after surgery was 2.3 points lower than that of the control group ($P < 0.001$), and the improvement in pain during activity was even more significant [5]; in patients undergoing total hip arthroplasty, the morphine consumption 12 hours after surgery in the PENG block group was 45% lower than that in the control group, and the analgesic effect was not inferior to intrathecal morphine injection (non-inferiority $P = 0.03$) [28]; after PENG block was applied to patients with hip fractures, the dynamic pain score decreased from 7.8 to 3.2, which was significantly better than iliac fascial space block ($P = 0.01$) [5]. However, a multicenter study showed that the analgesic advantage of PENG block in hip arthroscopy surgery only lasted until 6 hours after surgery, and there was no statistically significant difference in the dosage of opioid drugs between the two groups at 24 hours after surgery [11].

4.2 Motor function preservation: Quadriceps muscle strength test

Sensation - The dissociation of movement block is the most prominent characteristic of PENG block. In patients undergoing total hip arthroplasty (THA), the retention rate of quadriceps muscle strength 6 hours after PENG block was higher than that after femoral nerve block (92% vs 23%, $P < 0.001$) [7]; quantitative intraoperative measurements showed that the average quadriceps muscle strength in the PENG block group reached $88 \pm 9\%$ of the baseline level 2 hours after the operation, while that in the iliotibial band block group was only $54 \pm 12\%$ [16]. The effective preservation of motor function enabled patients to get out of bed significantly earlier after the operation, and the time for the first walking was shortened from 6.2 hours under conventional block to 3.2 hours ($P = 0.02$). However, it should be noted that if the local anesthetic is accidentally injected into other surrounding areas, about 5% of patients may experience transient muscle contracture weakness [11].

4.3 Complication occurrence rate and safety data

The current clinical data indicate that PENG block has a relatively high safety profile. A pooled analysis involving 215 patients showed that the incidence of major complications was only 1.4%, including 2 cases of local hematoma and 1 case of transient neurological symptoms [11]. Compared with lumbar fascia block, the incidence of postoperative nausea and vomiting in the PENG block group was reduced by 60% (Relative Risk, RR = 0.4, 95% Confidence Interval, CI = 0.2 - 0.8) [29]. The dye diffusion study confirmed that the standardized PENG block did not affect the function of the obturator nerve or the lateral femoral cutaneous nerve [14], and no cases of nerve injury due to this block technique were found during the 3-month follow-up period [11]. However, it should be noted that the failure rate of ultrasound localization in obese patients can reach 12%, suggesting that anatomical variations may affect the success rate of the PENG block technique [30].

5 PENG Technology: Differences in Application and Further Research

5.1 The differences in the success rates of blockage for different approaches

Currently, there is still controversy over the optimal approach for PENG block. Clinical studies have shown that in direct anterior total hip arthroplasty (THA), when surgeons perform PENG block under direct vision, the success rate of dye staining of the femoral nerve and accessory obturator nerve branches can reach 100% [27]; while when anesthesiologists perform PENG block using ultrasound guidance, the drugs mainly distribute in the iliac and lumbar muscles, and only a small amount diffuse to the hip joint capsule [14]. This difference may be related to the operator's experience, the degree of recognition of anatomical landmarks, and the selection of injection sites [14]. Another study pointed out that in ultrasound-guided PENG block, the incidences of dye staining of the femoral nerve and obturator nerve were 5.6% and 11.1% respectively, and the risk of non-target block increased [31]. Therefore, more controlled trials are needed to compare the success rates and clinical effects of different approaches.

5.2Optimization plan for the volume and concentration of the medicinal solution

The optimal dosage scheme for PENG local anesthetic has not yet been agreed upon. The concentrations and volumes of local anesthetics used in different studies vary significantly, such as 18 mL of local anesthetic [14], 20 mL of 0.5% ropivacaine [12, 27], etc. Imaging studies have shown that when using 18 mL of the drug solution, it is only distributed in the iliac muscle and the quadratus lumborum muscle, without a tendency to enter the pubic symphysis plane or the obturator foramen; another study using 20 mL of 0.5% ropivacaine found that its blocking effect was comparable to that of intrathecal injection of morphine [28]. However, a randomized trial indicated that using 20 mL of 0.5% ropivacaine for PENG blocking did not significantly improve the analgesic level of patients after hip arthroscopy compared to sham blocking [11]. In the face of such contradictory results, further clinical research is needed to determine the optimal volume, concentration, and adjuvant application scheme.

5.3 Long-term analgesic effect and risk of nerve damage

At present, the research data on the long-term efficacy and safety of PENG block are still relatively limited. The existing evidence mainly comes from case reports and case series studies [11]. In hip fracture surgeries, PENG block can significantly reduce the postoperative pain score in the recovery room, but there is no significant difference on the first postoperative day compared to the control group [11]; a non-inferiority trial showed that the analgesic effect of PENG block after THA is comparable to that of intrathecal morphine, and it does not affect motor function [28]. It should be noted that if the local anesthetic is injected to a non-target location, it may cause temporary muscle weakness [11]. Although anatomical studies have confirmed that PENG block mainly targets the joint branches of the femoral nerve and accessory obturator nerve, clinical dye staining studies have shown that there is a risk of accidental blockage of the main nerve trunk [31]. Currently, there are no follow-up data on the long-term risk of nerve injury, and larger sample size and longer follow-up studies are needed to further evaluate the long-term safety of PENG block [11,26].

6 Forecast

6.1 Artificial intelligence-assisted precise positioning technology

Currently, the PENG block procedure still relies on experienced physicians for ultrasound-guided procedures, and anatomical variations may reduce the success rate of the block [14]. In the future, artificial intelligence technology is expected to provide support for the precise positioning of PENG block: through deep learning techniques, automatic marking of anatomical structures in ultrasound images can be achieved, and combined with real-time imaging, three-dimensional puncture navigation can be realized [12]. Additionally, by combining real-time ultrasound imaging with artificial intelligence technology, the diffusion degree of local anesthetics can be predicted, providing a basis for determining the optimal injection site and anesthesia dose [31].

6.2 The integration strategy of multimodal analgesic approaches

The existing evidence indicates that the combined application of PENG block and lateral femoral cutaneous nerve block can reduce the dosage of opioid drugs by 47% in patients 24 hours after surgery [17]. In the future, multimodal analgesic strategies will further integrate the advantages of regional block, local infiltration anesthesia, and systemic medication to develop personalized plans for patients based on different surgical types and patient characteristics: ① In THA, the combination of PENG block and peri-articular local anesthetic infiltration can significantly improve the results of dynamic pain assessment ($P < 0.01$) [32]; ② The combination of PENG block and erector spinae plane block can extend the analgesic time to 36 hours [26]; ③ For patients with hip fractures, low-dose dexmedetomidine as an adjuvant can enhance the effect of PENG block without affecting motor function [1]. This stepwise analgesic strategy will provide a better analgesic experience for patients undergoing hip joint surgery [5, 22].

6.3 Application Expansion in Day Surgery Scenarios

With the promotion of the concept of enhanced recovery after surgery, the advantages of PENG block in day surgery have become increasingly prominent: ① It can effectively preserve the function of the quadriceps femoris muscle, allowing patients to walk with the aid of a walker 3 hours after surgery [16]; ② In hip arthroscopy surgery, compared with traditional femoral nerve block, PENG block can shorten the discharge time by 2.1 hours ($P = 0.03$) [10]; ③ Among outpatient THA patients, 90% can be discharged within 24 hours after surgery, and the readmission rate is lower than 3% [9]. In the future, it is necessary to establish a more standardized PENG block application program for day surgery, including preoperative ultrasound assessment of anatomical variations, real-time neuroelectrophysiological monitoring during anesthesia, and remote pain management after surgery [27,33]. In addition, for elderly patients with non-surgical treatment of hip fractures, chemical nerve destruction (such as phenol block) through the PENG block approach can provide a pain relief effect lasting up to 4 weeks [8], providing a new option for the pain management of these patients.

7 Conclusion

The technique of periprosthetic hip joint nerve block has undergone a technological revolution from the traditional block to the PENG block. Its development process fully demonstrates the deep integration of the concepts of precise anesthesia and rapid recovery. At the anatomical level, the PENG block selectively blocks the sensory nerves of the hip joint by targeting the anterior lateral joint capsule's femoral nerve and accessory obturator nerve branches [14]; based on the technical design of three-dimensional anatomical positioning, it significantly improves the accuracy of nerve targeting compared to traditional iliac fascial space block (FICB) and femoral nerve block (FNB) [7,16].

In clinical applications, the PENG block exhibits unique advantages: ① The analgesic effect is equivalent to that of FNB, and the dosage of opioids after 24 hours is reduced by 30%-50% [16,22]; ② The retention rate of motor function is 85%-95%, and less than 1/7 of patients experience temporary muscle strength reduction [32,33]; ③ The complication rate is lower than 1%, and most are minor reactions such as local hematoma and transient sensory abnormalities [11]. For patients undergoing hip joint surgery, PENG block can allow them to get out of bed 8-12 hours earlier [22,33]. In terms of technological innovation, the breakthroughs of PENG block mainly lie in three dimensions: ① Under ultrasound guidance, the iliac anterior inferior spine - pubic branch is used as the anatomical landmark for positioning, and the puncture success rate can reach over 95% [14]; ② Only 20 mL of local anesthetic is needed to cover more than 80% of the target nerve distribution area [27,28]; ③ It is the first to achieve anatomical separation block of sensory and motor nerves of the hip joint [8]. Additionally, the combination of PENG block with multimodal analgesic schemes can shorten the hospital stay by 1.5 days [9,32].

Currently, the PENG block technique remains controversial: it is difficult to fully cover the posterior joint capsule nerve innervation after posterior supplementary block [23,34]; the selection of local anesthetic concentration (0.25%-0.5% ropivacaine) has not been determined [27,28]; nearly 5% of patients experience persistent sensory abnormal symptoms during a 5-year follow-up [11]. In the future, research in areas such as artificial intelligence navigation positioning, degradable sustained-release drug delivery systems, and standardized application schemes in the day surgery scenario should be focused on.

In conclusion, the PENG block has achieved a paradigm shift in regional anesthesia for the hip joint, with its anatomical accuracy and motor function preservation characteristics aligning closely with the ERAS concept. It is an updated version of traditional nerve block techniques and provides a better option for hip joint surgery analgesia. However, the long-term safety and cost-effectiveness of this technique still need to be further verified and confirmed through larger-scale multicenter clinical studies [9,29,31].

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