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• Review Article •

Innovations and efficacy comparisons in minimally invasive techniques for dacryocystitis: from endoscopy to navigation

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HIGHLIGHTS

1. Critical Discoveries and Outcomes

• Minimally invasive techniques, particularly endoscopic dacryocystorhinostomy (Endo-DCR), have achieved clinical success rates of 85%-95%, comparable to or even surpassing those of traditional external approaches. These methods significantly reduce intraoperative bleeding, eliminate facial scarring, and better preserve lacrimal pump function. The identification of risk factors such as inferior turbinate hypertrophy and specific cytokine profiles (e.g., TGF-β2) associated with postoperative restenosis has opened new avenues for targeted intervention and long-term outcome optimization.

2. Methodological Innovations

• Technological advancements have introduced a range of novel surgical modalities, including laser dacryoplasty, microdrill-assisted osteotomy, and intraoperative image-guided navigation. The integration of artificial intelligence (AI) for preoperative image segmentation, robotic-assisted systems for precision control, and biodegradable drug-eluting stents for localized antifibrotic therapy marks a paradigm shift toward more intelligent and personalized lacrimal surgery. These innovations enhance surgical accuracy, safety, and reproducibility.

3. Prospective Applications and Future Directions

• The future of dacryocystitis management lies in the convergence of AI, robotics, and smart biomaterials. Emerging trends include AI-enhanced surgical navigation, machine learning-based risk prediction models, and pH-responsive stents for controlled drug release. The development of standardized training platforms (e.g.,

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Full Text

virtual reality simulators) and value-based healthcare models will support global dissemination and equitable access. The ultimate goal is to establish an integrated, patient-centered precision medicine framework that optimizes both clinical outcomes and healthcare efficiency.

Abstract: Dacryocystitis is a common disease caused by nasolacrimal duct obstruction. Traditionally, it has been treated with external dacryocystorhinostomy (Ex-DCR). But Ex-DCR has limitations, such as significant trauma and visible scarring. In recent years, minimally invasive techniques like endoscopic dacryocystorhinostomy (Endo-DCR), laser dacryoplasty, endoscopic microdrill-assisted osteotomy, and intraoperative navigation have significantly improved treatment outcomes. Endo-DCR has success rates of 85%-95%. It is better than laser techniques (70%-90%) and offers better cosmetic and recovery benefits. New technologies, including artificial intelligence (AI), robotic assistance, and biodegradable stents, are making surgery more precise and allowing for personalized treatment. Although the initial costs of minimally invasive techniques are higher, they can shorten hospital stays and improve recovery efficiency. So, they are very cost-effective in the long run. This is in line with the trends of "Value-Based Healthcare" and "Day-Case Surgery." This article provides a systematic assessment of the effectiveness, complications, and economic impact of various minimally invasive techniques and discusses future directions.

Keywords: dacryocystitis; endoscopic dacryocystorhinostomy; minimally invasive surgery; efficacy comparison; cost-effectiveness analysis

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Dacryocystitis is an infection of the lacrimal sac caused by nasolacrimal duct obstruction. Its main clinical symptoms are epiphora, purulent discharge, and even redness, swelling, and tenderness at the medial canthus. These symptoms seriously affect patients' quality of life.[1] The causes of dacryocystitis are many. The main ones are as follows: 1) The bony nasolacrimal duct is narrow anatomically. This has been suggested as an important risk factor;[1-3] 2) Chronic inflammation and the fibrosis that follows are seen as the basic pathological process that leads to the blockage of the lumen;[4-5] and 3) The local antimicrobial defenses are out of order, which involves changes in the expression of defensins and surfactant proteins.[6-7] If the infection is not controlled quickly, it may spread to surrounding tissues. This can lead to severe complications like orbital cellulitis or cavernous sinus thrombosis, and even permanent vision loss.[8] Therefore, an aggressive treatment strategy is needed, especially considering the changing pathogen profiles and the growing antimicrobial resistance. Recent epidemiological studies, like the six-year analysis of pediatric dacryocystitis in China, have provided new insights into pathogen distribution and resistance trends. This information provides guidance for targeted preventive and therapeutic strategies.[9]

Traditional treatments include antibiotics, lacrimal duct probing, or the gold-standard external dacryocystorhinostomy (Ex-DCR).[10] Ex-DCR requires a skin incision and has the risks of leaving an external scar and potentially disrupting the lacrimal pump. These traditional treatments have limitation. For example, they can cause significant trauma, facial scarring, and a long recovery time.

The appearance of minimally invasive surgical techniques has greatly improved the treatment situation. Among them, endoscopic dacryocysto rhinostomy (Endo-DCR) has become the main and first-choice minimally invasive procedure for most cases. It has established itself as the current standard for success. Techniques like Endo-DCR, laser dacryoplasty, endoscopic microdrill-assisted osteotomy, and intraoperative image-guided navigation have become popular trends. This is because they have advantages such as causing little trauma, enabling rapid recovery, and leaving no facial scarring.[11-12] A large-scale 20-year multi-institutional retrospective analysis further shows that the use of Endo-DCR (a minimally invasive method) is increasing. And its long-term success rates are similar to those of the traditional external method.[12] Current reviews suggest that the development of surgery in the ophthalmic and orbital field is moving towards intelligence and precision. Evidence shows that the integration of new technologies such as artificial intelligence (AI) and robotic-assisted systems is bringing new advances to minimally invasive surgical procedures.[13-15] At the same time, in the global policy environment emphasizes better healthcare resource allocation and cost control, the health economics value and accessibility of minimally invasive techniques have become important research topic. Recent Health Technology Assessment (HTA) reports offer evidence-based support for insurance reimbursement policies for these techniques.[16]

This review aims to systematically compare the efficacy, success rates, complications, and health economic benefits of different minimally invasive techniques. It mainly focuses on the well-established role of Endo-DCR. And it also looks into the current situation of frontier hotspots such as AI, robotics, and biomaterials. It provides an evidence base for clinical decision-making, and explores future research directions.

Pathophysiology and traditional treatments

Pathogenesis

The main pathological mechanism of dacryocystitis is lacrimal stasis caused by nasolacrimal duct obstruction. Obstruction can be congenital or acquired. The acquired kinds is often caused by inflammation, trauma, or anatomical anomalies. Stasis provides an environment for bacteria to grow (usually *Staphylococcus* and *Streptococcus*).

Recent studies on pathogen show that besides common Gram-positive bacteria (such as Staphylococcus and Streptococcus), the detection rates of Gram-negative bacteria (such as Haemophilus influenzae and Pseudomonas) and anaerobic bacteria are also high. The microbial spectrum is different between acute and chronic dacryocystitis and among different geographical populations.[17] A recent multicenter study found that the positive bacterial culture rate of lacrimal secretions in northwestern China (Kashi, 50.7%) was much higher than in southern China (Guangzhou, 26.0%). Also, the bacteria in the northwest was mainly Gram-positive cocci (71.4%), with a larger proportion of Streptococcus. In contrast southern regions had a much higher proportion of Gram-negative bacilli (37.6%), and Pseudomonas aeruginosa was more common. These differences may be closely related to climate, environment, and lifestyle factors. This highlights the importance of customized anti-infection strategies in different regions.[18]

In chronic dacryocystitis, the formation of bacterial biofilm formation is an important factor that causes the condition to persist and makes it resistant to treatment.[19] It is likely that this mechanism is also key in cases where underlying factors (such as certain drugs) lead to mucosal inflammation and narrowing. This then creates an environment that encourages biofilm-related infections. Recent studies on biofilm community structures using molecular biology techniques (for example, 16S rRNA sequencing) offer new ideas for developing targeted antimicrobial strategies.[20] This results in chronic inflammation, thickening, and scarring of the lacrimal sac wall. Eventually, it forms a mucocele or leads to acute suppurative infection.

Influencing factors

Key factors that affect treatment effectiveness include the location and severity of the obstruction, how long the disease has lasted, any previous surgical history, and whether there are nasal anatomical anomalies (for example, a deviated nasal septum).[21] In addition, the formation of dacryoliths (lacrimal stones) inside the sac or duct is another major cause of obstruction and infection. Analyzing their composition helps us understand changes in local microenvironment. Recently, the side effects of drug treatments have attracted attention. In particular, certain chemotherapy drugs (such as docetaxel, and 5-fluorouracil) and newer immune checkpoint inhibitors can cause nasal mucosal inflammation, metaplasia, or narrowing. This indirectly leads to secondary dacryocystitis. Moreover, recent studies have found that increased levels of certain cytokines, like transforming growth factor-beta (TGF-β) and vascular endothelial growth factor (VEGF), are closely related to postoperative scar overgrowth and restenosis. This provides potential targets for drug treatment. Lee et al.[22] prospectively analyzed tear cytokine profiles after endoscopic DCR. They found that eyes with surgical recurrence had significantly higher levels of TGF-β2 and fibroblast growth factor-2 (FGF-2) compared to those with successful outcomes ($P < 0.005$ for both) . This direct evidence shows that TGF-β signaling is involved in the development of ostial fibrosis and restenosis. Although this study lacks direct evidence linking VEGF to DCR failure, VEGF is well known as a key pro-fibrotic factor in other ocular tissues. Anti-VEGF drugs are already used clinically to manage corneal scarring. These findings suggest that drugs targeting TGF-β or VEGF pathways, such as topical losartan (a TGF-β inhibitor) or anti-VEGF antibodies, show promise as additional therapies to prevent postoperative restenosis after DCR.

Diagnosis

The diagnosis of dacryocystitis is mainly based on typical clinical symptoms (for example, excessive tearing, purulent discharge, redness/tenderness at the inner corner of the eye) along with physical examination. Lacrimal irrigation can confirm the presence and approximate location of the obstruction. Nasal endoscopy is very important for assessing the nasal anatomy, ruling out space-occupying lesions, and planning endoscopic surgery.[21]

While making the diagnosis, it is necessary to distinguish it from conditions that have similar clinical features. Canaliculitis is especially important. It often shows swelling and tenderness over the canaliculus, along with purulent discharge or concretions (sulfur granules). Pressing on the lacrimal sac usually does not result in the expression of pus, which helps differentiate it from dacryocystitis. More importantly, space-occupying lesions of the lacrimal system or rare nasal obstructions can exactly mimic chronic dacryocystitis, leading to misdiagnosis. For example, papillomas of the lacrimal sac or nose (such as fungiform or inverted papilloma), although benign, can cause obstruction and secondary infection. The acute symptoms are indistinguishable from those of ordinary bacterial dacryocystitis. In addition, rare causes like rhinoliths can block the lower end of the nasolacrimal duct, causing classic symptoms of chronic dacryocystitis. These can be easily missed without a careful nasal assessment.[23] For patients who do not respond well to treatment, have atypical symptoms, or have masses discovered during surgery, a high level of suspicion for such conditions is needed. The diagnosis should be confirmed through imaging (such as MRI, CT) and routine intraoperative biopsy, as this directly affects the treatment strategy and prognosis.

Traditional treatments and limitations

Traditional treatments have major limitations. Lacrimal probing and balloon dilation are minimally invasive but only suitable for simple stenoses. For complete obstructions or chronic fibrosis, the restenosis rate is high, and the long-term effectiveness is poor.

Ex-DCR used to be the surgical "gold standard." This method requires a skin incision and division of the medial canthal tendon. This inevitably causes facial scarring, significant bleeding during the operation, and risks damaging the medial canthal vessels and the tendon. More importantly, damage to the orbicularis oculi muscle and subsequent scarring from the incision may disrupt the "lacrimal pump" mechanism, which is essential for tear drainage. This could potentially lead to persistent excessive tearing even with an open ostium. Although high-quality evidence shows that Ex-DCR has a better success rate than Endo-DCR, the latter has advantages such as being minimal invasive, having less bleeding, and requiring a shorter surgical time,[24] The cosmetic result of Ex-DCR can be a problem. One study reported that 27.5% of patients and 42.5% of examiners considered the resulting facial scars to be cosmetically significant.[25] This problem is especially obvious in younger and dark-skinned patients, who are more likely to have visible scars.[25] For people with high cosmetic demands, the Endo-DCR approach, which avoids any external skin incision completely, naturally becomes the preferred and often the only first choice to eliminate the risk of a visible scar. As a result, minimally invasive endoscopic techniques have replaced Ex-DCR as a first-line procedure.

The shortcomings of these traditional techniques, including cosmetic problems, significant tissue damage, disruption of functional structures, and poor adaptability to complex cases, precisely led to the development of minimally invasive techniques. Endo-DCR access the area through natural passages, perfectly avoiding facial scars and maximally preserving the integrity of the lacrimal pump system and medial canthal anatomy. This overcomes traditional limitations and achieves more precise and physiologically appropriate surgical results.

However, it must be noted that Ex-DCR still has irreplaceable value in specific complex cases, especially those that are difficult to manage endoscopically. For cases with severely disrupted anatomy due to major facial trauma (such as naso-orbito-ethmoidal fractures), displaced bony landmarks, or an ectopic lacrimal sac, Ex-DCR provides a wide surgical field for precise reconstruction and localization of the displaced sac.[26] Moreover, for revision surgery after a failed endoscopic DCR, if widespread nasal scarring or other pathologies prevent reconstruction of the bony window, Ex-DCR can bypass the affected area to create a new drainage pathway.[27] For lacrimal sac tumors or malignancies (such as lymphoma, squamous cell carcinoma), which often look like inflammatory stenosis, Ex-DCR offers the necessary exposure for thorough resection and obtaining a definitive pathological diagnosis.[28] Thus, Ex-DCR is changing from the former "gold standard" to a "precision tool" for managing specific complex anatomies, revision surgeries, and oncological diseases. Its clinical value has been redefined in the era of precision medicine.

Overview of minimally invasive techniques

With the progress of technology, minimally invasive surgical treatment for dacryocystitis has developed a lot. It, mainly aims to improve success rates, reduce trauma, and enhance patient experience.

Endoscopic dacryocystorhinostomy (Endo-DCR)

Endo-DCR is the main minimally invasive procedure now. Its technical idea is to use a nasal endoscope through the natural nasal passage to find the lacrimal sac in the corresponding area of the middle meatus. Then, it opens the bone and lacrimal sac mucosa to create a new tear drainage pathway. Since it became widely used in the 1990s, this technique has become the first choice in many medical centers. It has advantages like no skin incision, no facial scarring, little intraoperative bleeding, less tissue damage, and preservation of the medial canthal tendon and lacrimal pump function. But it has a hard learning curve, and its success rate depends on the surgeon's experience, nasal anatomy, and the nature of the lacrimal sac disease. As a technological platform, endoscopy is often used together with laser, microdrill, and other techniques to deal with more complex cases, which will be described in detail later.

Also, to find a more physiological and simple procedure, endoscopic low-position dacryocysto-rhinostomy (En-LP-DCR) has been studied in recent years. This technique creates a lower bony window near the physiological nasolacrimal duct opening below the axilla of the middle turbinate. It aims to reduce bone removal and better preserve lacrimal sac integrity and pump function. Initial clinical reports show that En-LP-DCR combined with new split-type lacrimal stents (such as RT type) can be done without powered drills. This significantly shortens operative time, and its success rates are similar to those of traditional Endo-DCR. It offers a new option for patients with specific anatomical conditions.[29]

Laser dacryoplasty

Laser technology provides a high-precision way to manage lacrimal duct obstruction. Laser dacryoplasty is made to recanalize the original duct, lasers are also important in transcanalicular laser-assisted dacryocystorhinostomy (TL-DCR/TcL-DCR). Laser dacryoplasty uses lasers like holmium to vaporize or remove obstructive tissue with little bleeding under endoscopic guidance. This makes it especially suitable for membranous or mild cicatricial obstructions, or as an addition to Endo-DCR. However, using it alone is limited because of the risk of restenosis caused by inflammation from thermal injury. To reduce this risk, putting in a silicone stent after the operation is a very important extra step. A network meta-analysis mentioned in a recent systematic review shows that stenting greatly improves surgical results by keeping the lumen open during the important healing phase in various DCR procedures.[30] But, the overall success rate of TL-DCR has been found to be lower than that of the EX-DCR,[31] and whether silicone intubation works well specifically in TL-DCR is still being debated. This might be because of the special features of the laser technique. So, the choice of laser procedure and the decision to use extra stent must be made according to the nature of the obstruction, the surgical technique chosen, and individual patient factors. Also, because of its high equipment costs, laser dacryoplasty is generally seen as a useful addition to broader endoscopic techniques rather than a procedure on its own.

It is most commonly used together with nasal endoscopy. With the good view provided by the nasal endoscope, lasers (such as holmium) can be used to precisely vaporize scar tissue or open fibrotic obstructions. This method is suitable for revision surgery or cases with dense scarring. It has the advantages of precise operation and less bleeding, but requires careful control of thermal injury to prevent restenosis.[32]

Endoscopic microdrill-assisted osteotomy

The microdrill has become a very useful tool in endoscopic lacrimal surgery. It is used for both osteotomy and duct recanalization. In DCR, microdrill-assisted osteotomy is a big improvement over traditional bone chiseling. High-speed electric or pneumatic microdrills can quickly and precisely grind away the bone of the frontal process of the maxilla and lacrimal bone to show the lacrimal sac. This is especially helpful in cases with unusually thick bone walls.

There is a different minimally invasive procedure called transcanalicular microdrill dacryoplasty (MDP). In this procedure, a small microdrill is used under endoscopy to mechanically remove obstructive tissue from inside the original nasolacrimal duct. The aim is to recanalize it without creating a new bony ostium.[33] This way of keeping the anatomy intact offers a scar-free alternative to DCR for some cases, although its long-term success rate is just moderate. The choice between these techniques—creating a new bypass with microdrill osteotomy in DCR or recanalizing the original pathway with microdrill dacryoplasty—depends on the level, nature, and severity of the obstruction.

This technique is basically a very efficient and safe step in Endo-DCR surgery for dealing with bony obstruction or a thickened frontal process of the maxilla. It has advantages like high bone removal efficiency and little trauma, but it needs thorough irrigation to remove bone debris. With intraoperative image navigation, surgeons can safely use the microdrill on thick bone in complex anatomical areas, greatly reducing the risk of entering the orbit or skull base.[34]

Compared to traditional instruments, microdrills have low vibration and are highly controllable. This reduces accidental damage to the surrounding mucosa and bone structures, improving surgical safety and efficiency.[33] Importantly, a complete endoscopic DCR must deal with the distal nasolacrimal duct, especially the area of Hasner's valve. This principle of ensuring the valve level is open is important not only when creating a new opening in DCR but also in primary procedures for congenital obstructions. Endoscopic incision of an imperforate Hasner's valve alone has been shown to have high success rates. Not opening this final part properly is a known cause of persistent epiphora after a DCR that is technically successful in other ways. The precision of the microdrill allows controlled enlargement of the nasal opening in a posterior-inferior direction towards the valve site. This ensures a widely open drainage pathway and reduces the risk of postoperative failure from sump syndrome or stenosis at the important distal opening.[35]

Intraoperative image-guided navigation

Intraoperative Image-Guided Navigation is a new area in precision lacrimal surgery. This technology combines preoperative CT or MRI images with real-time intraoperative endoscopic view. It gives the surgeon the exact three-dimensional position of instruments within the complex sinus and lacrimal anatomy through optical or electromagnetic tracking systems. For complex cases with previous surgical failure, abnormal nasal anatomy, or extensive disease, navigation technology can accurately find the lacrimal sac. It can avoid damaging important structures like orbital contents and the skull base, and greatly improve surgical safety and success rates. The use of real-time imaging technology is key to future progress in surgical intelligence and standardization.[36] Using advanced imaging is very important for making surgical navigation more useful in complex lacrimal surgery. Traditional methods, such as 3D CT-dacryocystography (CT-DCG), have been successfully used to show the lacrimal drainage system during surgery. They serve as an important guide in cases with severely changed anatomy.[37] Based on this, recent progress has added AI-based automatic image segmentation into navigation systems. Studies on paranasal sinus segmentation, like those using hybrid CNN-Transformer architectures, have shown the ability to automatically outline complex sinus structures and surgical landmarks from standard preoperative CT scans. This is a big change from methods that rely on contrast. It reduces the surgeon's need to reply on manual anatomical identification and improves navigation accuracy, consistency, and ease of use. Evidence from segmentation performance studies shows that such AI-driven methods can improve the outlining of important anatomical boundaries. This is basic for improving localization accuracy in navigation systems and has the potential to make surgical workflows more efficient.[38]

This technology is mainly for cases with complex anatomy, revision surgery, or high-risk patients. It is often used together with endoscopy or microdrill techniques. It greatly improves surgical precision and safety by providing real-time 3D localization. It does not directly affect patency rates but improves surgical outcomes by reducing severe complications. However, it is expensive and takes more time for preoperative preparation.

Integration and standardization of minimally invasive technologies

As individual minimally invasive techniques have become well-developed, the focus has moved to their strategic integration and standardization. This is to get the best outcomes, make ensure the procedure can be repeated, and help them be widely used. This section discusses how technologies work well together and the important role of standardized procedures.

Evaluation of combined techniques

To deal with the limitations of single techniques, using multiple minimally invasive technologies together has become an important way to manage complex dacryocystitis cases and improves surgical success rates.[38] This combination aims to make use of the advantages of each technique, creating a combined effect that works better than each one alone. For example, the combination of "Navigation + Endoscopy/Microdrill" greatly improves safety in surgeries with complex anatomy. It is suitable for cases with anatomical anomalies, revision surgery, and high-risk situations. Its advantages are precise positioning and better safety, but it has problems like high cost and long preparation time.

At present, the most advanced combined model is

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the "AI Navigation + Robotic Assistance + Endoscopy" system. This system uses AI algorithms to process imaging data and plan surgical routes. Then it uses robotic arms to carry out endoscopic operations and control instruments steadily and accurately. It is expected to take surgical accuracy and safety to a new level, especially in deep and anatomically complex areas. However, it is very expensive, the technology is not yet fully developed, and it is still in the exploratory stage.[38]

Combined treatment, through the complementary nature of technologies, improves surgical precision and safety and broadens the range of cases for minimally invasive surgery. Potential risks include longer operative time, higher costs, and greater demands on the surgeon's skills and equipment.

Technique standardization and clinical promotion

The importance of Standardized Operating Procedures (SOPs) in getting consistent result is shown by the learning curve for Endo-DCR. Surgeons only consistently achieved success rates >90% after mastering the procedure through about 30 cases. This shows how standardized protocols ensure quality and help spread skills.[39]

Standardized preoperative evaluation is the foundation. It requires figuring out the obstruction site and nasal anatomy through nasal endoscopy and imaging to rule out surgical contraindications. New digital tools are now an important part of this process. For example, 3D reconstructions from CT scans, including those seen in Virtual Reality environments, are used to improve understanding of anatomy. Furthermore, AI-based image analysis can automatically measure important parameters like bone wall thickness and vascular landmarks, providing objective data support and strengthening the role of technology in digital SOPs.

Standardizing intraoperative procedures is crucial. This includes: 1) Standardized anesthesia (general or local); 2) The same key surgical steps: identifying the middle meatus, precisely locating the lacrimal sac, creating a bony window of an adequately sized (≥10 mm), creating and anastomosing mucosal flaps; 3) Standardized use of equipment, such as 0° or 30° nasal endoscopes, micro-instruments, and powered systems (e.g., microdrill).[40]

Postoperative care also needs to be standardized. This includes regular nasal cleaning, lacrimal irrigation, standard use of antibiotic and corticosteroid nasal sprays, and the same follow-up time points (e.g., 1 week, 1 month, 3 months after surgery) to check for patency.[41] Moreover, postoperative risk prediction tools developed using machine learning models can predict the risk of restenosis for each patient based on factors like patient age, surgical method, and intraoperative conditions. This helps guide the intensity of follow-up and the timing of intervention for high-risk groups.[42]

Standardized protocols, by optimizing key steps, greatly improve surgical success rates and reduce the risk of complications such as ostium closure and bleeding.[42]

For clinical promotion, SOPs shorten the learning curve, reduce differences in techniques among surgeons, and allow more medical centers to perform these techniques safely and effectively. The development and use of internationally standardized assessment tools, like the Ophthalmology Surgical Competency Assessment Rubric (OSCAR), are examples of this. They provide objective standards for training, making surgical techniques more uniform and facilitating their global spread.[43] The appearance of virtual reality (VR) and augmented reality (AR) simulation training platforms greatly helps with standardized training. They let doctors practice repeatedly in a risk-free digital environment, significantly shortening the time it takes to acquire skills.[44-45]

Comprehensive efficacy assessment

Different minimally invasive techniques have different principles, so they have different indications and clinical results. To evaluate their advantages and disadvantages in a systematic way, this section gives a comparison and analysis point by point based on indications, success rates, complications, and recovery time.

Indications and success rates of different minimally invasive techniques

Endo-DCR is now the most common procedure and has the widest range of indications. It is especially good for most cases of nasolacrimal duct obstruction (NLDO) and chronic dacryocystitis, and it has high success rates. Its main problems include postoperative ostium granuloma, synechiae, and re-obstruction.

Using laser (e.g., holmium) as an additional treatment is more suitable for membranous obstruction or for stopping bleeding and removing scars. But if it is used alone, it may cause higher restenosis rates because of thermal damage, so its long-term success is relatively limited.[46]

Endoscopic microdrill-assisted osteotomy is an important additional treatment for cases of bony nasal passage stenosis. It greatly improves the efficiency and safety of bone removal. For complex anatomy, revision surgery, or high-risk patients, intraoperative image-guided navigation makes surgery more precise and safer. It helps avoid serious complications, and thus indirectly protects the surgical result.[34-35]

Postoperative recovery and quality of life improvement

The improvement in patients' quality of life brought by minimally invasive techniques is mainly seen in postoperative recovery. Compared with traditional external surgery, all minimally invasive techniques prevent facial scarring. Because there are less tissue damage and bleeding, postoperative pain is less severe, and swelling goes away faster. The average recovery time for patients is much shorter than that of traditional methods.[47] Evaluation studies using reliable questionnaires (e.g., NLDO-QOL) show that postoperative scores in social function and emotional well-being areas improve much more in the Endo-DCR group than in the Ex-DCR group.[48] Common minor postoperative problems include temporary nosebleeds and nasal synechiae. These can usually be fixed with simple treatment and have a small impact on quality of life.

The challenge of postoperative re-obstruction and countermeasures

Postoperative lacrimal duct re-obstruction is still the most important factor affecting long-term effectiveness and quality of life. Its occurrence rate is closely related to surgical technique, ostium size, and the quality of postoperative care. A recent retrospective study on 90 patients further showed that inferior turbinate hypertrophy is an independent risk factor for En-DCR failure (OR=4.6). It may cause ostium re-obstruction by taking up space in the middle meatus, affecting the distribution of postoperative nasal sprays and increasing the risk of local inflammation. This study also found that putting a silicone tube in the nose during surgery as a routine is not a factor protects and improves prognosis.[49]

To deal with the problem of restenosis, researchers are actively working on local drug delivery systems. For example, biodegradable stents loaded with anti-proliferative agents like mitomycin C or anti-VEGF drugs can release the drugs locally and continuously for several weeks. This can effectively stop fibroblast proliferation and scar formation.[50] Early clinical studies indicate that this method has the potential to greatly improve long-term patency rates.[51-52]

Health economics of minimally invasive treatments

Besides clinical success, it's very important to evaluate the economic aspects of these treatments. From the point of health economics, although the direct cost of a single minimally invasive surgery for dacryocystitis may be higher than that of traditional surgery, its overall cost-effectiveness is remarkable.

Optimization of medical costs

Minimally invasive surgeries (e.g., Endo-DCR) are often done as day-case or outpatient procedures. This means patients do not need to stay in the hospital, and it leads to a big drop in medical costs. Studies show that using this method makes hospitalization costs for Endo-DCR much lower than those for the traditional Ex-DCR.[53]

At the same time, patients recover faster after these surgeries (on average 1-2 weeks). So they can go back to work and their daily lives sooner. This, also greatly cut down the indirect social costs caused by lost productivity.

In the long run, the higher success rates and lower recurrence rates of minimally invasive surgery mean patients do not need secondary surgeries, long-term medication, and frequent follow-ups because of treatment failure on complications. So it reduces long-term healthcare resource use and individual's financial burden. Health economic analyses support this claim. They show that, even though there may be small difference in success rates, endoscopic techniques are most cost-effective. This is they are more operationally efficient, have higher rates of day-case surgery, and rely less on general anesthesia, which leads to an overall reduction in systemic healthcare costs.[54-56]

Enhancement of overall healthcare system efficiency

For the whole healthcare system, promoting minimally invasive technologies helps make better use of resources, improve how quickly operating rooms are used, and shorten the time patients wait. This makes medical service delivery more efficient at the system level.[57] This benefit well with the "Value-Based Healthcare" and "Day-Case Surgery First" health policies that many countries are promoting.[58] By moving elective minimally invasive surgeries from inpatient departments to day surgery centers, healthcare systems can use limited bed resources more efficiently to deal with a larger number of surgeries.

Challenges and prospects for technology promotion

However, the first investment in minimally invasive technologies is large. This includes the cost of expensive endoscopic systems, laser equipment, navigation platforms, and specialized training. This makes it hard for resource-limited regions to access these technologies.[59] This "technology gap" has become a global health policy issue. The World Health Organization (WHO) and HTA agencies in some countries have started to focus on how to lower the barrier for low- and middle-income regions to get these technologies. They do this through innovative financing models, technology transfer, and centralized procurement. For example, they have developed customized value frameworks for rapid health technology assessment. These frameworks are designed to help make evidence-informed decisions and make better use of resources in resource-constrained settings, as shown by recent implementations in countries like Argentina.[60] But the long-term benefits and improvements in system efficiency they bring show a positive outlook for cost-effectiveness.

Future directions and research gaps

Current studies on dacryocystorhinostomy often report short-term results using different quality-of-life measurement methods.[61] This shows that there is a need for long-term efficacy comparisons and standardized assessments to make the evidence base for clinical decisions stronger. Studies like the one by Zheng et al.[62] have clearly shown the clinical advantages of current techniques such as endoscopic DCR. But in the future, development should focus on thoroughly optimizing these existing technologies and creatively combining advanced technologies to further improve results.

Optimization of existing technologies and clinical promotion

This direction aims to tackle the main challenges that current minimally invasive technologies face in practical use. The main job is to set up long-term, multi-center efficacy databases. These databases will be used for comparative studies on the patency rates of techniques like Endo-DCR, laser dacryoplasty and endoscopic microdrill techniques over 10 years or more. Also, a gold standard for evaluating postoperative quality of life needs to be established. Lowering technological and cost barriers is crucial for ensuring equal access. In the future, we need to develop cost-effective surgical equipment and instruments. And we should set up standardized training systems. For example, we can use tools like virtual reality simulators, which have been proven to shorten the learning curve.[63] This can help doctors in resource-limited areas master core techniques. There are also research gaps in standardized postoperative care. For example, we still need large-sample study to find out the best plan for concentration and timing of anti-scarring agents (e.g., mitomycin C). Health policy research should look into how to incorporate minimally invasive techniques into primary healthcare systems and design reasonable medical insurance payment methods to encourage their use.[64]

Breakthrough prospects and challenges of biodegradable drug-eluting stents

Postoperative anastomotic fibrosis is a major challenge that affects the long-term success of dacryocystitis surgery. Biodegradable drug-eluting stents, by combining material science and local pharmacology in an innovative way, offer a new way to actively control tissue healing. It is important to note that the value of this platform technology has been proven in other surgical fields. For example, although polymer-free drug-eluting stents (such as Zilver PTX) are available, a study by Soga et al.[65] shows that when used to treat lower limb arterial disease, they may lead to much higher late lumen loss and restenosis rates compared to their polymer-coated counterparts. And as shown in the study by Oliveira et al. mentioned in the review, combining PVA with PP mesh makes the surface more hydrophilic and promotes angiogenesis. This shows the potential of new biomaterial-mesh composites to improve tissue healing in abdominal wall repair. This technology uses biodegradable materials like poly(L-lactic acid) (PLLA) as carriers. These carriers can provide local and sustained release of anti-fibrotic drugs (e.g., rapamycin) while supporting the ostium. A key factor for the success of such systems is that adding drug can greatly change the physical and chemical properties of the polymer carrier. For example, adding ibuprofen to acrylic polymers can reduce its glass transition temperature. Optimizing this interaction ensures that the stent has good mechanical integrity during implantation and degrades in a controlled way. In the end, it achieves an integrated process of "treatment-degradation-no trace.[66]

Research on biodegradable drug-eluting stents has shown that they can reduce scar formation by locally releasing anti-proliferative agents. Preclinical and clinical evaluations show that this technology is a promising way to lower restenosis rates, especially in difficult clinical situations.[50-51]

However, there are still challenges in applying this technology in clinical practice. Precisely matching the drug release rate with the tissue healing process is very important. It requires a balance between effectiveness and tissue toxicity. Also, making the stent degradation rate match the tissue remodeling cycle is an important factor for success.[67] Future research directions include developing intelligent response systems. For example, Guo et al.[68] (2024) proposed a pH-responsive hydrogel stent. It can intelligently adjust drug delivery according to changes in the local microenvironment. Moreover, the combination of AI and nanotechnology brings new breakthroughs to stent technology. By using machine learning algorithms to optimize the design of nano-drug delivery systems, AI can predict drug release rate. This enables more precise controlled release, maximizing the anti-scarring effects and minimizing side effects.[69]

Although there is still a need to optimize drug release control and degradation kinetics, this technology is an important step towards precision and minimally invasive treatment for dacryocystitis. It is likely to significantly improve long-term success rate of surgery.

Integration of artificial intelligence and emerging technologies

AI and machine learning (ML) technologies offer new chances for making dacryocystitis surgery more precise and personalized. Deep learning-based image segmentation models can automatically find key sinonasal and skull base structures (e.g., the optic nerve) in CT scans. This has great potential to improve pre-operative planning and risk assessment processes.[70-71] During surgery, AI-enhanced navigation systems can combine 3D models with real-time endoscopic views. They can provide dynamic anatomical positioning and safety warnings, greatly improving operational safety in complex cases.[72]

After surgery, statistical models and machine learning algorithms can build predictive models. These models can assess individual's risk of stenosis by analyzing clinical data. For example, Liang et al. [73] developed and verified a nomogram that includes factors like the triglyceride-glucose index and diabetes status for this purpose. This provides a basis for personalized postoperative intervention. Recent reviews point out the new role of multimodal large language models. These models can combine radiological images, clinical text, and electronic health records to support diagnostic and decision-making tasks.[74]

Robotic-assisted surgery systems are another new area. Although there is no commercial system specifically designed for lacrimal surgery yet, general-purpose sinonasal and skull base surgical robots have shown great potential for precise manipulation in small spaces, such as precise control of laser probes or drills. Future applications may include semi-automated ostium formation. The use of robotic systems in lacrimal surgery looks promising. However, just like the challenges seen in other areas of robotic surgery,[75] major obstacles related to their safety, cost-effectiveness, and regulatory procedures must be overcome first. These are expected to be key development points in the near future.

Conclusion

Minimally invasive surgery has firmly become the best option for dacryocystitis treatment. Among these methods, Endo-DCR has a success rate of 85%-95%. It also has a short recovery period of 1-2 weeks, and the great advantage of leaving no facial scars. So it has become the first choice for most patients. However, its promotion and use still face the problem of regional differences. The application range of traditional Ex-DCR is gradually focusing on specific complex cases.

At present, the field is at a turning point. The future development must go in two directions: First, we need to make the treatment more accessible, reduce costs, and gather high-level evidence through technological innovation (such as robotics and intelligent navigation) and operational standardization. Second, we should rely on integration of different disciplines. We should bring together clinical, engineering, and data science teams to jointly promote the development of next-generation intelligent surgical systems.

In the end, all efforts will aim at a patient-centered goal. We will build an integrated "one-stop" precision treatment model. This model will combine AI-based precise planning, intraoperative real-time robotic navigation, and personalized postoperative management. In this way, we can maximize the therapeutic effect and efficiency.[76] This integrated, patient-centered approach not only meets the core goal of precision medicine but also perfectly fits the principles of "Value-Based Healthcare" mentioned earlier. It ensures that technological advancements lead to real improvements in patient outcomes, care efficiency, and overall value in healthcare delivery.

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(III) Provision of study materials or patients: Both authors
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