1 Spinal Endoscopy: Historical Review and Current Applications

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1.1 Nomenclature and Terminology

The term "endoscopy" implies the use of a thin, tubular and coaxial surgical instrument that contains image transmission, illumination, and frequently also irrigation and a working channel. Such an instrument is placed into the surgical field via a small stab incision and by means of tissue dilation. The image is produced by a camera at the end of the optical system and transmitted to a monitor. In the spine and different to endoscopy of preformed body cavities, the very limited surgical space is constantly irrigated to maintain visibility, to control bleeding, to cool tissue when radiofrequency or laser are being used, and to wash out surgical debris.

These specific features distinguish "true" endoscopy (or "full endoscopy" as termed by Ruetten) from tubular microendoscopy, where a small retractor or working tube is placed and surgery is performed "in the dry" and with standard microsurgical instruments under camera vision. Examples for the latter technique could be the Storz "Destandau" system or the more recently developed Storz "Easy-Go system."

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Another synonym for "full endoscopy" that is commonly used in the Asian literature is "working channel endoscopy," which stresses the fact that such modern coaxial endoscopes contain an instrument channel beyond the rod lens, the illumination, and the irrigation channel.

Frequently used technical descriptions in the context of endoscopy are "percutaneous" or "minimally invasive." However, these terms are not truly meaningful since all surgery (apart from superficial dermatological surgery) is in principle percutaneous and since no generally accepted definition of "minimal invasiveness" exists. Provided that the term "endoscopic" is used precisely and appropriately, no further qualifying adjectives should be required to explain the nature of the surgical approach and the type of surgical endoscope used.

Another conceptual problem tends to be the implied but not spelled-out inclusion of one specific anatomic approach into the name of a surgical technique. A very good example would be the acronym PELD for "percutaneous endoscopic lumbar discectomy." PELD typically implies that the traditional transforaminal approach is used. However, many pathologies that can be treated by means of "transforaminal" PELD can equally or sometimes even better be addressed using an interlaminar or in certain cases a transosseous (burr hole) approach.

This terminological imprecision tends to be further complicated by the indiscriminate use of

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the term "discectomy," which is not what microscopic or endoscopic spine surgeons perform these days. Probably the only surgical techniques that actually do achieve an almost complete discectomy are the ALIF procedure or a total lumbar disc replacement (TDR). With spinal endoscopy, sequestrations, disc fragments, or herniations are extracted under direct vision and the acronyms and terms we use should reflect that.

In the same line of thinking, the terms "foraminoplasty" or "annuloplasty" really do not confer a precise image of what is being done during an operation and we should all aim at being as precise and anatomically correct as possible when describing and naming surgical procedures.

1.2 Brief History of General Endoscopy and Arthroscopy

It has been a longstanding desire of researchers, medical doctors, and other curious individuals to look inside the human body and its cavities. The word "endoscopy" is derived from two Greek roots: ἔνδον (éndon) = inside and σκοπεῖν (skopein) = to observe.

As for modern medical applications, Philipp Bozzini in the early nineteenth century was the pioneer who first invented a candle-illuminated device to inspect ears, urethra, and rectum [1]. In 1853, the French physician Desormeaux developed a more advanced device for very similar applications and for the first time the term "endoscope" was documented in the 1855 proceedings of the French Academy of Sciences [2]. Desormeaux also spent significant effort into propagating the technology and therefore is known as "the father of endoscopy."

But it required the invention of the electric light bulb (Edison 1879), of more advanced rod lens systems (Hopkins 1960), and of the CCD camera (Boyle and Smith 1970) to truly make these early endoscopes anywhere nearly as useful as we know them to be today.

However, even before the introduction of CCD cameras into medicine, Kenji Tagaki and Masaki Watanabe from Japan developed a series of ever better "arthroscopes," first for veterinary use, but after the second world war increasingly also for human use and in 1950, the first human knee joint was arthroscopically examined. Based on their experience with 300 patients, Watanabe, Takeda, and Ikeuchi published the first *Atlas of Arthroscopy* in 1957 [3]. It is not by chance that Watanabe is known as the "father of arthroscopy" and since spinal endoscopy derives itself from arthroscopy, he may very well also be seen as a "grandfather of spinal endoscopy."

1.3 The Development of Spinal Endoscopy

Initially, the lumbar spine with its rather common pathology disc herniation was the target of the se new "percutaneous" approaches. The first of these approaches to lumbar disc herniations, however, were "blind" procedures in terms of direct visualization, since neither Kambin nor Hijikata [4] used endoscopes in their early work in the 1970s. In the following period of innovation, APLD (automated percutaneous lumbar discectomy) [5] became the "in"-procedure and this technique also led to a patent. The major disadvantage of not having visual control was soon recognized, though, and only a few years after the first optical images from within a lumbar disc had been published [6], the procedure that we nowadays know as "discography" was inaugurated by Kambin [7] as well as by Schreiber et al. [8]. This fluoroscopy- and contrast-controlled injection of indigo carmine into the disc continues to be one of the most valuable steps in improving intraoperative accuracy and anatomic identification of the surgical target under endoscopic view.

While interest in "blind" percutaneous procedures with the purpose of disc volume reduction continued with the focus of interest shifting from APLD towards laser decompression [9], the surgical desire for full visual control, advanced technical accuracy, and precise surgical targeting in a parallel development pushed the advancement from arthroscopy to spinal endoscopy. Probably one particularly interesting early paper in this sense was the report on endoscopically guided laser application on non-sequestrated disc herniations in 6 patients by Mayer et al. [10]. They termed their new technique PELD (percutaneous endoscopic laser discectomy), an acronym that nowadays mostly is used for an endoscopic surgical technique. In 2001, Knight published his experience on endoscopy-guided foraminal nerve root decompression and used the term "foraminoplasty" for his technique [11].

An important step in the development of spinal endoscopy with respect to the original transforaminal approach was the anatomic definition of the "safe working zone" (also known as "Kambin's triangle") between the descending, exiting nerve root as the antero-superior limitation, the ascending facet as the posterior limitation, and the lateral border of the superior endplate of a motion segments' inferior vertebra as the inferior limitation by Kambin and Zhou [12].

This safe entry zone into the disc, the colorization of nucleus material with indigo carmine together with improved endoscopes and working tools inaugurated the first phase of major global interest in spinal endoscopy—at the time termed "percutaneous arthroscopic disc surgery."

The knowledge concerning the anatomy of the safe triangle and tools to trim the anterior aspect of the ascending facet also permitted for larger endoscopes and cannulas to be employed, which made surgical decompression more efficient.

Initially, bilateral biportal access was used—much like in knee arthroscopy. When Schreiber first used an angled optical system, visibility of the posterior annulus region with these early intradiscal ("all inside" and "inside-out" strategies) was significantly improved [8]. Kambin et al. published on their experience on 59 patients operated on with the biportal technique and on 116 patients operated on with the more modern, unilateral and uniportal technique [13].

Yeung did major work on improving the devices available with his YESS system, from which several current endoscopic systems are derived and published on a large (albeit uncontrolled) personal series with posterolateral transforaminal endoscopic decompression of disc herniations and lateral recess stenosis [14, 15].

Based on the pioneering work described above, a more differentiated and specific approach to spinal pathologies became possible while at the same time, MRI diagnostics had become more readily available in the developed world. The primary intradiscal approach ("in-out-technique") had been abandoned by most surgeons and disc extrusions, free sequestrations, and migrated fragments had become the targets of visually controlled surgery. In 2005, Schubert and Hoogland published their results with a large series (2-year-FU on 558 of 611 patients, no controls) of lumbar disc herniations, operated on by transforaminal endoscopy [16]. During the same period, variations of the original transforaminal approach were developed and the osteoclastic widening of the foraminal passage enabled more directional variety when entering the canal [17]. These developments in turn necessitated a more anatomically specific and approach-oriented classification of the pathologies to be treated by spinal endoscopy and the paper by Lee et al. was seminal in this process [18]. The same group also published on the technical specificities when addressing extraforaminal herniations [19]. Ruetten et al. expanded the panel of practically usable endoscopic approaches to the lumbar spine by describing the far-lateral transforaminal approach [20] as well as by adding the interlaminar lumbar approach in analogy to the traditional microsurgical approach to the lumbar spinal canal [21].

While non-visualized (only controlled by fluoroscopy) percutaneous cervical procedures (lasers, mechanical decompression) were attempted early, cervical endoscopy lagged behind lumbar endoscopy mostly because of the lack of suitable endoscopic systems. Only after the turn of the millennium did smaller caliber and shorter coaxial systems with good optics, illumination, and a reasonable working channel become available. Prior to that, Fontanella had started to use a 4.6 mm working cannula through which he worked with rigid or flexible endoscopes for visualization and with microsurgical instruments. He published his personal series of 171 patients who underwent anterior and posterior cervical disc surgeries in this fashion [22]. It is to the credit of the surgeons from Seoul's Wooridul Spine Hospital that the first series of percutaneous endoscopic cervical discectomy (PECD) via the anterior approach and using a working channel endoscope was published [23]. The posterior interlaminar approach to cervical pathology (in analogy to the microsurgical Frykholm procedure, [24]) was published in 2007 by Ruetten et al. [25].

Already in the early years of spinal endoscopy, Leu et al. pioneered techniques for endoscopic lumbar interbody fusions [26, 27]. In those early series, the stabilization required was obtained with a transpedicular external fixator, which most likely was the main reason why interest in this approach subsided again. In 2004, Gastambide began the endoscopic transforaminal placement of specially designed titanium cages without additional fixation, but reported a considerable complication rate [28].

1.4 Currently Available Evidence from Controlled Studies

The past decade has seen several high-quality controlled and randomized-controlled studies that compared endoscopic surgery with standard, microsurgical procedures for cervical and for lumbar pathologies. Most of these studies have been analyzed and discussed for a 2013 review article [29].

The pathologies treated in these controlled comparisons were:

- Primary cervical disc herniations with radiculopathy (posterior endoscopic foraminotomy vs. ACDF) [30]
- Primary lumbar disc herniations (transforaminal or interlaminar endoscopic sequestrectomy vs. microsurgical sequestrectomy) [31]
- Recurrent lumbar disc herniations (transforaminal or interlaminar endoscopic revision surgery vs. microsurgical revision surgery) [32]
- Recurrent lumbar disc herniations (transforaminal endoscopic revision surgery vs. microsurgical revision surgery) [33]
- Cervical disc herniations with radiculopathy (anterior endoscopic decompression vs. ACDF) [34]
- Lumbar lateral recess stenosis (interlaminar endoscopic decompression vs. microsurgical decompression) [35]
- Lumbar central canal stenosis (bilateral interlaminar endoscopic decompression vs. bilateral microsurgical decompression) [36]

The majority of these studies report 2 years of follow-up with clinical outcomes that are largely equivalent to those with microsurgical standard procedures and with fewer and fewer serious complications in the endoscopy group. There was a tendency towards higher reoperation rates with endoscopy in some studies, despite the fact that these RCTs uniformly were performed by experts in the field [31, 33]. Other short-term benefits of endoscopy were less blood loss, shorter operation times, shorter hospital stays/faster return to work, and less postoperative pain.

No long-term outcomes in comparison to microsurgery (e.g., in relation to progression to fusion or to adjacent segment degeneration) have been reported from these trials as of yet.

1.5 Current Clinical Applications of Spinal Endoscopy

In the lumbar spine, disc herniations, recurrent herniations, and migrated sequestrations are routinely being addressed by transforaminal or interlaminar endoscopic techniques. Foraminal stenoses and zygapophyseal cysts are frequently treated by spinal endoscopy. There also is an increasing body of literature showing that the decompression of lumbar central spinal canal stenosis can very well be accomplished by endoscopy.

There currently appears to be interest in performing lumbar and iliosacral medial branch and dorsal branch ablations under endoscopic vision as opposed to the traditional fluoroscopy-supported techniques.

In the cervical spine, the anterior transdiscal as well as the posterior interlaminar approaches for the endoscopic treatment of disc herniations and foraminal stenoses are firmly established. One recent case report describes a further evolution of the transcorporeal microsurgical approach originally described by Choi [37, 38]. The authors passed an endoscope through the burr hole and performed the extraction of a migrated disc herniation and direct endoscopic control [39]. In contrast to the lumbar spine, there is no relevant published work on the endoscopic treatment of spinal canal stenoses with associated myelomalacia. The same applies to stenoses caused by a calcified PLL.

In the thoracic spine, the endoscopic approaches and techniques that are routine in the lumbar and in the cervical spine are much less standardized and established. In addition, there is a crossover between these techniques and microsurgery as well as with the established, video-assisted surgical techniques that have long been employed for the treatment of fractures, infections, and the anterior release in scoliosis surgery. The relevant endoscopic publications in that arena therefore are mostly case series. With symptomatic disc herniations and stenoses being frequent in the cervical and lumbar spine while remaining comparatively rare in the thoracic spine, this is most likely not to change very soon.

In addition to the approaches and techniques mentioned above, there is a body of published experience with transnasal and transoral endoscopic approaches to the upper cervical spine and to the craniocervical junction. Again, these are typically case reports or small case series on pathologies ranging from tumors to infections, degeneration, and inflammatory conditions. Overall, these techniques represent a transition between classic spinal endoscopy and ENT endoscopy.

As far as surgical instruments are concerned, articulated high-speed burrs, probes, and rongeurs enlarge the actual working space that can be reached within the visual field of an endoscope. Slightly larger systems with a wider working channel have made the endoscopic treatment of lumbar central canal stenosis more efficient and less time-consuming.

In terms of tissue ablation and tissue modulation, side-firing lasers maintain a strong position in those countries, where billing and reimbursement structures allow for the considerable cost of these systems to be recovered. Alternatively, the radiofrequency probes used for hemostasis are often also capable of shrinking, modulating, and ablating soft tissues, but cannot vaporize bone.

Despite all efforts, endoscopic lumbar interbody fusion has so far not been able to establish itself as a viable alternative to open or mini-open techniques and this for a number of reasons. The transforaminal endoscopic approach—even when performed bilaterally—entails size limitations for surgical tools, interbody cages, and bone grafting. Cages with a small footprint, limited cage expandability, difficulty in performing a complete evacuation of the nucleus, and an optimal preparation of the endplates all contribute to a lesser reconstruction of disc space height, a higher chance for subsidence, and/or insufficient fusion. Since currently much attention is given to lordosis reconstruction in the context of lumbar fusions, endoscopic transforaminal lumbar fusion is facing an uphill battle.

1.6 Outlook

One of the greatest perceived limitations of spinal endoscopy (and for that matter of endoscopy in principle) is the current lack of true 3-dimensional vision and hence of a precise appreciation for the depth of the visual field.

It is probable that some surgeons consider this a greater problem than others and it is also likely that the capabilities of a human brain to "3-D-navigate within a 2-D-image" vary significantly between individuals. Another factor is certainly the type of training received during residency and fellowship: Someone who has professionally "grown up" using an operating microscope will possibly find the 2-dimensional space of an endoscopic image less easy to conquer than another surgeon who has routinely arthroscoped knees, shoulders, and other joints before becoming a spinal specialist.

Within the coming years, however, this technological limitation should increasingly be overcome by the current developments in advanced stereoscopic ultra-HD cameras and suitable optics. These will deliver a true 3-dimensional view from within the spinal canal while preserving a key advantage of endoscopy, which is to have the surgeon's eye right next to the pathology and to avoid the typical problem of deep, narrow operating fields that limit the usable angle of vision for microscopes. This will probably represent the fall of the last relevant technical barrier for a wider acceptance of spinal endoscopy, also outside the countries that have led the way for decades now.

It appears likely that the endoscopic treatment of lumbar spinal canal stenoses and disc hernations will expand further. After all, symptomatic lumbar spinal canal stenoses and disc herniations together constitute a large portion of lumbar degenerative conditions requiring treatment, and the group of patients in need of surgical treatment for these conditions is getting older, more comorbid, and more obese in many industrialized countries. With faster operations, shorter hospital stays, the option of performing many of these procedures under conscious sedation, and with obesity being no obstacle to endoscopic techniques, the current period might constitute a historical turning point in the relative popularity of microsurgical and endoscopic approaches.

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