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# The evaluation of ultrasound imaging for neuraxial anesthesia

EPIDURAL anesthesia and analgesia are particularly powerful instruments in obstetrics, acute pain management, and chronic pain therapy. However, conventional epidural techniques continue to be plagued by significant limitations.[1] The failure rate of epidural anesthesia in obstetrics is estimated to range between 6–25%.[2,3] For acute postoperative analgesia, the failure rate may lie between 30–50%.[4–7] Failure to access the epidural space may be secondary to challenging anatomy or the experience and skill of the anesthesiologist.[8–10] Inadequate analgesia or anesthesia experienced with catheters in the epidural space may have a variety of causes[1] including catheter migration out of the 'posterior' epidural space, space occupying masses, placing the epidural catheter at an inappropriate level based on unreliable surface landmarks,[11] and maldistribution of drugs delivered into the epidural space. The evolution of ultrasound (US) technology has provided a tool that can circumvent some of the inherent limitations of conventional epidural anesthesia/analgesia. The anatomy of the spinal column and the epidural space can be reviewed reliably and quickly with US prior to the performance of an epidural. Needles can be inserted into the epidural space under direct observation or after a planned trajectory subsequent to a review of the relevant anatomy. Catheters can be inserted into the epidural space under direct observation and directed where they are needed with US guidance. The distribution of medication delivered into the epidural space can be observed with US and this information correlated with clinical effect.

## Historical perspective

Because of ossification of the vertebral column, ultrasonography of this area has been neglected. Cork[12] was the first anesthesiologist to describe a hypodense area within the lumbar intervertebral interspace. He assumed that US imaging would be a powerful technique that would enable visualization of the epidural space. Further work on the use of US imaging was presented by Currie,[13] Wallace,[14] and Bonazzi.[15] In 1984, Currie examined 75 female patients who received an epidural anesthetic for obstetrics. With the help of 5-MHz-transducers, the expected puncture depth of the epidural space was determined and compared to the values measured during the procedure. Currie found a high correlation between the results of both measurements. In 1992, Wallace published the results of a prospective study involving 36 female patients whose lumbar spinal anatomy was evaluated with US. This study demonstrated that the structures in the lumbar spine could be reliably identified with US. Both Currie and Wallace defined "laminae" as hyperdense structures on US and the epidural space as a hypoechogenic area. In a similar study, Bonazzi examined 40 adult male patients in whom an epidural anesthetic was administered for hernia repair.[15] Bonazzi discovered a hyperechogenic structure, which he identified as ligamentum flavum. He defined the consecutive hypoechogenic structures between the shadows of the bones as epidural space. In these first analyses of US imaging data on the lumbar spine, a close relation between US-measured and puncture-related depth was shown. The main limitation of these early studies was the poor resolution of the US images. This has remained the main restriction on introducing US technology into everyday clinical use for neuraxial anesthesia/analgesia.

## US equipment – current status of the technology

To achieve adequate resolution of imaging of very thin and detailed structures it is necessary to use a high frequency US probe. With the use of these high frequency probes the penetration depth of the beam is reduced. Since most of the puncture activities related to neuraxial applications in adults take place in a region of 3 to 9 cm, the use of probes from 4 to 11 MHz is effective. These probes are able to produce high quality imaging and resolution and have the correct range for clinical activities in neuraxial anesthesia. We found that linear probes were most efficient for

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FIGURE 1 The Kretz 600™ (on the left) is a portable and compact ultrasound system with a 5-MHz-probe. The Kretz 6000™ ultrasound system is a digital ultrasound system with a very efficient BW-scan quality. It can be used with up to three different ultrasound probes.

FIGURE 2 The General Electric LQ400™ ultrasound system with colour Doppler imaging and the possibility of digital beamforming.The system can be run with probes from 2 to 11 MHz and the data are processed digitally. Diverse clinical adaptations and applications are possible.

the presentation of the neuraxial anatomy. Images obtained with these probes can identify the ideal puncture point, the puncture direction, and the distance from the skin to the epidural space or the ligamentum flavum. US probes from Kretz were electronic probes and the system from General Electric (GE) had digital US probes and beam forming. In our studies we used three different US systems. We were able to use conventional systems like the Kretz 600™ for simple measurements of distances. With the more advanced systems, like the Kretz 6000c™ (with a 5-MHz slightly curved array probe) we were able to reach sufficient quality for the demonstartion of bone and ligamental structures (Figure 1). These systems enabled us a view of the dura mater and the intrathecal space. With the use of the digital US system LQ 400™ from GE (Solingen) with 7-MHz and 4-MHz probes we were able to improve imaging especially in the ligamental structures and near the bone (Figure 2). We were able to bypass the technical limitations by using software adaptations to improve the imaging system. This helped us to demonstrate nerve structures and vessels of the spinal region.

**Studies conducted by our group - introduction**

Our studies have focused on the direct application of US technology to facilitate neuraxial procedures. We have expanded on the concepts and observations of Currie, Wallace, and Bonazzi in developing imaging techniques that improve diagnostic and procedural capabilities in the lumbar and thoracic spine. Our primary focus has been to identify the causes of failure in epidural anesthesia/analgesia and to use US to facilitate quality improvement in this field. For example, data obtained from US images can be used to facilitate epidural puncture and catheter placement. This in turn improves the quality of analgesia obtained via the epidural catheter and enhances patient satisfaction.

In our first clinical studies, the basic sonomorphology of the lumbar epidural space was described in female obstetric patients.[16] Following this early work, techniques for the improvement of the puncture process were developed.[17,18] This process was exacting and took considerable effort and time. However, we were eventually able to define the expected puncture angle and the expected puncture depth in the lumbar epidural space.[16] Subsequent investigations focused on the sonomorphology of the thoracic epidural space and prospective, randomized studies were performed to evaluate the effects of US imaging on puncture performance, the quality of analgesia/anesthesia, and patient satisfaction.[8,19,20]

I will present an overview of existing data on US imaging in neuraxial anesthesia/analgesia (Figures 3–6).

### Measurement of the expected puncture depth with US – median access

In an examination of pregnant patients, with and without active labor, the correlation between ultrasonographically measured data on the depth of the lumbar epidural space and direct measurement at the time of lumbar puncture ranged between 0.79–0.92.[21] We determined the effect of axis deviations of the spinal column on puncture data and quality of regional anesthesia. We defined the role of pressure on the US probe on the precision of the measurements of measured *vs* puncture data. In addition, we studied the effects of pregnancy and patient movement on the quality of US imaging.[16,21]

### Measurement and definition of other relevant puncture criteria

The course traversed by the needle and the depth of penetration of the epidural space are not only dependent upon the point of puncture, as determined by the ultrasonographically determined shortest distance in the median plane, but are also dependent on the angle of trajectory of the needle.[22] As the actual angle of needle penetration may vary from the ultrasonic angle used to estimate puncture depth, an error of from 10–30% in the estimated puncture depth may occur. A correction factor can be used to more reliably estimate the true puncture depth; $1/\cos\alpha$ ($\alpha$ = ultrasonographic angle). Therefore, it is necessary to emphasize that a distinction must be made between expected (i.e., ultrasonographic) and actual (i.e., actual needle trajectory) puncture angles, especially when the puncture angle is oblique. This three-dimensional variability of the puncture angles *vs* the measured and expected angles is defined as "precision" of the measurement. Precision will remain a problem until US equipment is designed to allow simultaneous real-time needle insertion under US guidance using a single probe.

### Influence of diagnostic US on the quality of regional anesthesia

We studied the effects of diagnostic US on the quality of regional anesthesia in three prospective, randomized studies.[8,19,20] We randomized patients into two groups. In the imaging group US data were used to determine puncture point, puncture angle, and puncture depth to determine an "optimum" needle trajectory. In the control group, the epidural puncture was done without prior US identification of relevant anatomy. A LOR technique via a Tuohy needle was used to identify epidural puncture in both groups.

We found a significant reduction (approximately 35%) in the number of puncture attempts and in the number of puncture planes accessed (approximately 15%) in the US group compared to the conventional group. Visual analogue scale pain scores and patient satisfaction both showed a clear improvement (about 30–50%) related to treatment with US-guided punctures.

### Paramedian access

Initial work with US was done using a median access plane, as this is the traditional plane used to access the lumbar epidural space clinically. We managed to vastly improve the quality of imaging when we experimented with a paramedian access plane. With the paramedian access plane we minimized the influence of calcified structures in the US field and expanded the utilization of the foramina intervertebrae as "visible windows."[17] The enlargement of the "visual window" by paramedian access resulted in improved visibility and enhanced detail of structures in the intraspinal space. Imaging of dura mater and intrathecal nerve structures were significantly improved by this method.[17] We were able to optimally demonstrate vessels in the epidural space using both BW scan and colour Doppler [especially for small venous (low flow) vessels].[18] Use of the paramedian access plane allowed us to closely evaluate the sonomorphology and the needle trajectory of the 'tightly covered' thoracic epidural space.[23] We used the paramedian access plane to develop a method of "real-time" puncture guidance and monitoring.[24] This was the first description of a "real-time" epidural puncture. We found it was possible to visualize dural tears related to the occurrence of postdural-puncture-headaches and to place an epidural blood patch under US guidance. We have studied the impact of "real-time" imaging in patients receiving combined spinal-epidural (CSE) anesthesia and found there were improvements in needle guiding and puncture quality (unpublished data).

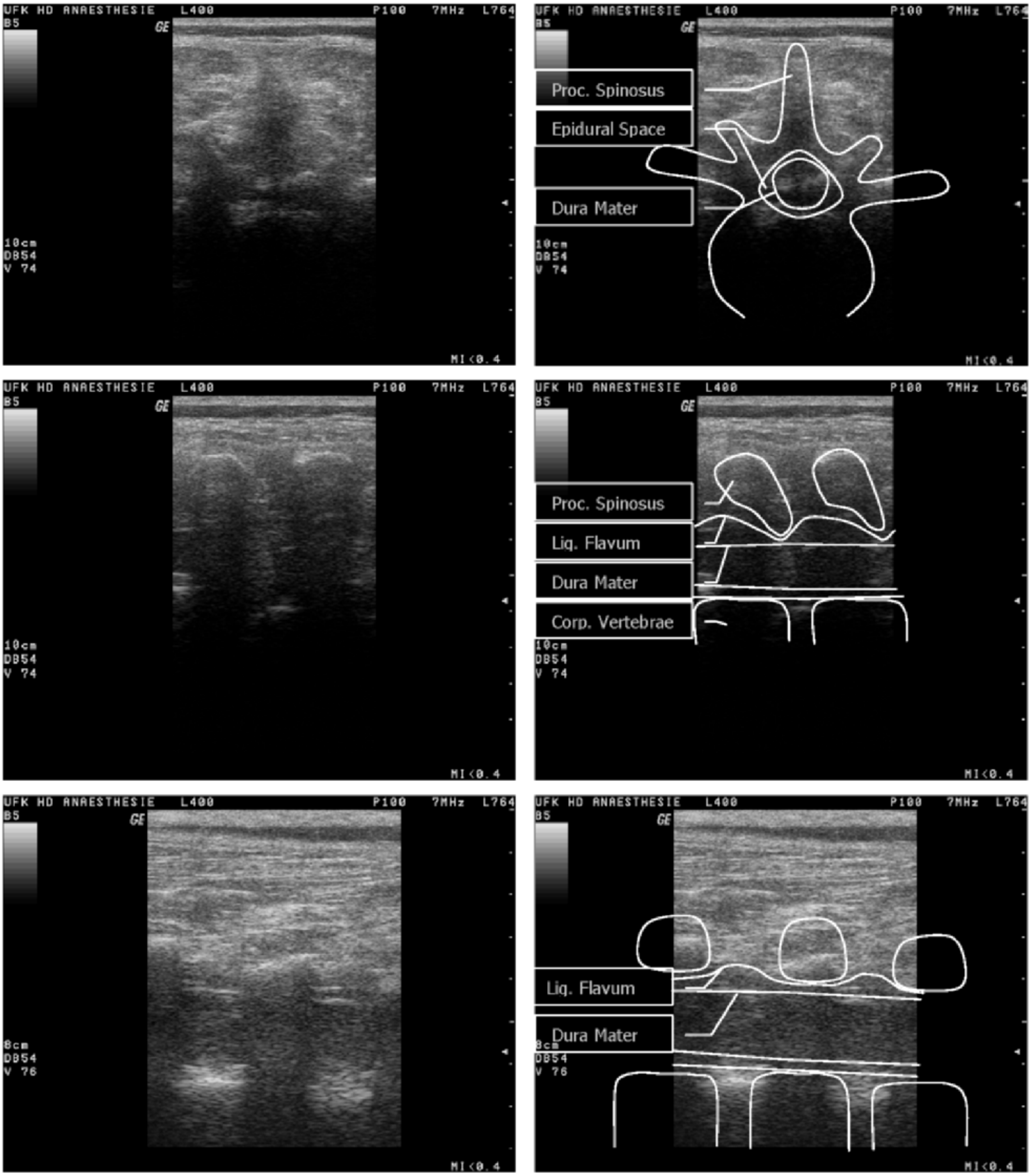


FIGURE 3 Overview of lumbar transversal and longitudinal median and paramedian structures. On the left side we demonstrate an original ultrasound picture; on the right side is a line drawing and description of the sonomorphology of the intraspinal space.

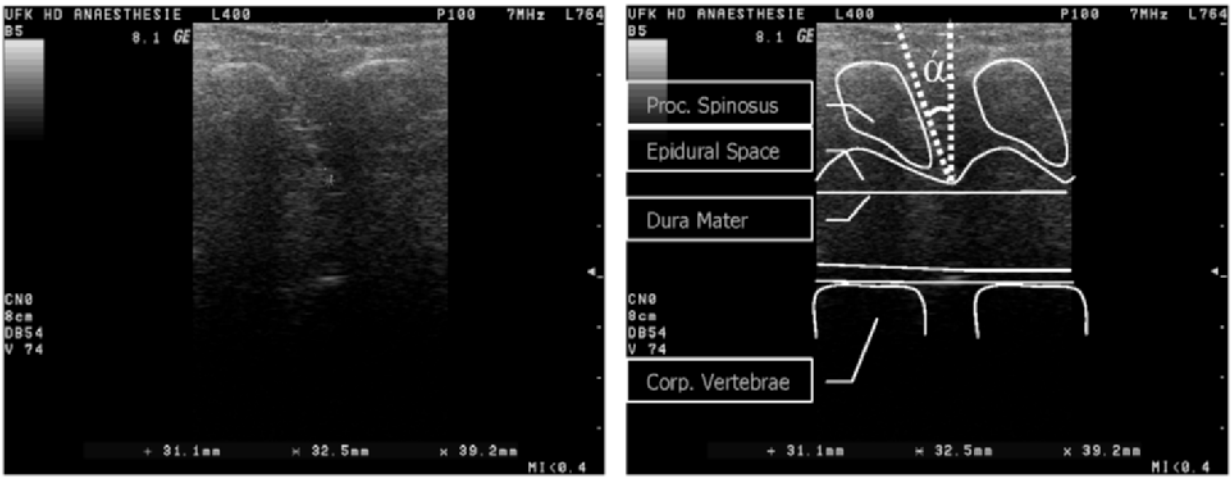


FIGURE 4 Overview of the longitudinal median needle trajectory. On the left side we demonstrate an original ultrasound picture; on the right side a line drawing is shown.

**Applications of ultrasonography in neuraxial anesthesia/analgesia**

We have demonstrated that US can be used to evaluate epidural anatomy, to facilitate epidural puncture, and to improve analgesia/anesthesia and patient satisfaction. In addition, in our study of 300 obstetric patients we found significantly fewer side effects among patients in the US group.[20] There were reductions in mild and severe headaches and in back pain. Paresthesia and blood in the catheter were found infrequently in the US-guided group.

US can be used to survey relevant anatomy before epidural puncture and to determine the exact level of needle penetration. Anatomic variations can be identified before they are a cause of frustration or complications (e.g., unanticipated "shallow" epidural space "wet tap"). The needle trajectory can be accurately predicted or, with "real-time" imaging, observed directly. The anesthesiologist, particularly in challenging patients, encounters less frustration. Patient satisfaction is increased as they are exposed to fewer needle punctures. The quality of anesthesia and analgesia are improved, likely by more accurate positioning of the epidural catheter. Vascular and neural structures can be easily identified and thereby avoided. In two large studies, Auroy[25] and Horlocker[26] reported a connection between the appearance of paresthesia and the insertion of epidural needles. A study by Puolakka[27] showed that sensory effects following epidural analgesia appear frequently but are temporary, consistent with the findings of Scherer[28] who found no persisting neurological sequelae following epidural anesthesia. The more purposeful positioning of the Tuohy needle and the guided placement of the catheter by US may reduce the occurrence of nerve root irritation and subsequent temporary or permanent neurologic deficits.[19]

Education and familiarization with relevant anatomy with the help of US may accelerate the learning curve for epidural catheterization in situations where US is unavailable. US may prove to be a valuable "screening" tool before, during, and after epidural catheterization. US machines are portable and are generally available in most hospitals in comparison to CAT scan or magnetic resonance imaging. Dural puncture sites can be readily identified. Space occupying masses in the epidural space can be visualized (e.g., fat, blood, abscess).

**Limitations of ultrasonography used for neuraxial anesthesia/analgesia**

Training is required to properly utilize US technology. The same limitation applies to transesophageal echocardiograpy (TEE). To my knowledge, formal training programs are not available in Canada or the United States. European countries are leading the way in this application of US technology. Formal training is available in several centres in Europe (e.g., Vienna, Austria; Heidelberg, Germany; Berlin, Germany). To use US effectively one must master the principles and the theory of the technology, accumulate experience with the equipment and with the techniques utilized in neuraxial anesthesia/analgesia, and have a detailed knowledge of the relevant anatomy. The learning curve for the described applications has not been described.

| Working group | Patients | cases | Correlations-coeff. | Puncture depth [mm] | Bland-Altmann-analysis [mm] | Correlations-coeff. | Puncture angle [°] | Bland-Altmann-analysis [°] |
|---|---|---|---|---|---|---|---|---|
| Cork 1980 [15] | Epidural anesthesia | 29 | $r^2 = 0{,}95$ | 45,0 ± 5,8 | 2,64 | - | - | - |
| Curie 1984 [18] | Epidural anesthesia for delivery | 75 | $r^2 = 0{,}92$ | 41,2 ± 8,1 | 5,4 | - | - | - |
| Wallace 1992 [75] | Epidural anesthesia for cesarean sectio | 36 | $r^2 = 0{,}98$ | 55,1 ± 20,6 | 5,4 | - | - | - |
| Bonazzi 1995 [11] | Male Herniotomia | 40 | $r^2 = 0{,}98$ | 51,0 ± 6,2 | No data | - | - | - |
| Grau 2001 [26] | Epidural anesthesia in obstetrics | 100 | $r^2 = 0{,}79$ | 53,0 ± 7,0 | 6,8 | $R^2 = 0{,}13$ | 15,10 ± 7,1 | 13,4 |
| Grau 2002 [32] | Epidural anesthesia in obstetrics | 150 | $r^2 = 0{,}83$ | 51,2 ± 9,2 | 6,9 | $r^2 = 0{,}14$ | 14,80 ± 6,7 | 13,2 |
| Grau 2001 [30] | CSE for cesarean sectio | 40 | $r^2 = 0{,}92$ | 51,5 ± 9,3 | 5,1 | $r^2 = 0{,}07$ | 12,25 ± 5,0 | 10,2 |
| Grau 2001 [31] | Difficult epidural anesthesia in obstetrics | 36 | $r^2 = 0{,}87$ | 57,5 ± 11 | 7,7 | $r^2 = 0{,}31$ | 16,20 ± 7,5 | 12,7 |

FIGURE 5 Prediction of the puncture depth and the puncture angles related to ultrasound examinations of the lumbar epidural space.

Although this fact will slow the widespread adoption of routine US use for neuraxial techniques, we do not feel this is a serious limitation as we are convinced the advantages of US merit the extra effort required to gain proficiency and that that proficiency can be gained quickly, particularly as US technology evolves.

Acquisition and maintenance of an US machine, training, and technical support are costly. However, any assessment of cost-benefit must also account for improvements in the quality of patient care delivered, reduction in the frequency and severity of associated complications, enhanced education and teaching, benefits of research dependent on US technology, and shared costs (e.g., US can be used to facilitate vascular access, TEE, trauma assessment, facilitate and improve peripheral regional anesthesia/analgesia,[29] etc.). In special circumstances US may have a clear role in enhancing patient safety (e.g., if an epidural is to be placed in an uncooperative, heavily sedated, or anesthetized pediatric or trauma patient). We are currently working on a cost-utility analysis of US-guided regional anesthesia to demonstrate that US has a valuable economic impact.

Additional time is required for an US investigation before the performance of an epidural or CSE. However, the additional time requirement is no more than five minutes in experienced hands. The shortening of the time required for the actual performance of the epidural technique outweighs this delay resulting in a clear time saving, particularly in difficult cases (poor or misleading surface landmarks).[10]

US technology has some limitations. Imaging resolution is limited to a maximum depth of 6–8 cm for spinal US. US access is impeded by the surrounding bony structures, which impair imaging possibilities by reflection and reduced sound expansion. Therefore, US machines used for intraspinal US must use probes of 5–8 MHz frequencies. With this wavelength, the resolution in the sound field falls to 0.2–0.6 mm.

Spinal column anatomy restricts the utility of US. The "windows" that can be used for an US investigation of the spinal column are very small, especially in the thoracic spine. Therefore, it is fundamentally difficult to acquire a complete overview of the epidural space via a number of "sound-based windows." Furthermore, it is technically difficult to acquire a "real-time" assessment of US guided neuraxial procedures because of the small nature of the acoustic window. Simultaneous puncture and imaging processes cannot be performed in this restricted field. Although "real-time" imaging is possible under some circumstances, US technology has not advanced to allow the

| Working group | Patients | Number and group | Number of puncture attempts | Number of neccesary puncture plains | Quality of analgesia VAS Score | Patients satisfaction Verbal rating score |
|---|---|---|---|---|---|---|
| Grau 2002 [32] | Epidural anesthesia for delivery and cesarean sectio | ultrasound 150 | 1,37 ± 0,7 | 1,14 ± 0,37 | 0,76 ± 1,4 | 1,23 ± 0,45 |
| | | 150 control | 2,18 ± 1,1 | 1,28 ± 0,55 | 1,37 ± 2,3 | 1,81 ± 0,93 |
| | | Significance % effect of improvement | p < 0,013 37,2% | p < 0,001 10,94% | p < 0,006 44,53% | p < 0,001 30,28% |
| Grau 2001 [30] | CSE for cesarean sectio | Ultrasound 40 | 1,27 ± 0,5 | 1,00 ± 0,00 | 0,3 ± 0,9 | 1,4 ± 0,6 |
| | | 40 control | 2,10 ± 0,92 | 1,17 ± 0,44 | 1,13 ± 2,1 | 1,8 ± 0,72 |
| | | Significance % effect of improvement | p < 0,001 39,53% | p < 0,04 14,53% | p < 0,033 73,45% | p < 0,006 22,22% |
| Grau 2001 [31] | Difficult epidural anesthesia in obstetrics | ultrasound 36 | 1,5 ± 0,9 | 1,27 ± 0,5 | 0,8 ± 1,4 | 1,3 ± 0,5 |
| | | 36 control | 2,6 ± 1,4 | 1,5 ± 0,7 | 1,8 ± 2,7 | 2,1 ± 1,3 |
| | | Significance % effect of improvement | p < 0,001 42,31% | p < 0,05 15,33% | p < 0,035 55,56% | p < 0,006 38,10% |

FIGURE 6 Influence of the diagnostic ultrasound on the quality of epidural anesthesia or combined spinal epidural anesthesia in comparison to control groups.

uniform application of this concept in neuraxial anesthesia/analgesia. The use of two planes, one for imaging and one for interventional access, is associated with obvious limitations – interventional activities must be assisted by a second person!

The needles and catheters currently used for epidural anesthesia are not optimized for US examination and are poorly visualized on US. With the introduction of "optimized" materials (e.g., US sensitive wire-reinforced epidural catheters) that are hyperechoic it will be possible to better visualize these structures. This may help us to guide the catheters where we wish them to go with the use of US.

It is difficult to double-blind US trials. Unblinded studies enhance the risk of bias. Both the researcher and the proband or patient are able to influence the results. This fact may restrict the relevance and impact of clinical studies. However, attempts are being made to address these methodological problems.

## Conclusions

The implementation of US imaging can revolutionize regional anesthesia. There are diverse applications. Quality improvements in epidural and peripheral[29] regional anesthesia/analgesia can be achieved. Teaching is enhanced and learning curves may be shortened. US may facilitate research that may eventually help make regional anesthesia more efficacious and safer than it already is. Side effects and complications may be reduced and when a complication occurs it may be more readily identified and controlled treatment may be possible with US guidance (e.g., epidural blood patch). Continuing evolution of US technology may further expand the potential for US in regional anesthesia/analgesia.

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