

# 8 Complications of Brachial Plexus Anesthesia

Brendan T. Finucane and Ban C.H. Tsui

---

In 1884, Carl Köller<sup>1</sup> discovered the local anesthetic properties of cocaine while working with Sigmund Freud. This was one of the most important discoveries in the history of medicine. In that very same year, Halsted<sup>2</sup> performed the first documented case of brachial plexus anesthesia at Johns Hopkins hospital when he injected the brachial plexus in the supraclavicular region under direct vision. The first percutaneous approach to the brachial plexus was performed by Hirschel<sup>3</sup> in 1911, when he injected local anesthetic drugs into the axillary sheath. In that same year, Kulenkampff<sup>4</sup> described the classic supraclavicular approach to the brachial plexus. Axillary approaches to the brachial plexus have always been more popular than supraclavicular techniques, perhaps because the risks seemed to be fewer.

More than 120 years have elapsed since brachial plexus anesthesia was first performed and since that time there have been numerous anecdotal reports of complications. In preparation for this update of the first edition, the author has searched the literature for the past 8 years, in an attempt to report the most common and most serious complications of brachial plexus anesthesia. Although it has only been 8 years since the first edition of this book was published, some interesting developments have taken place in the intervening period. One of the most important new developments has been the progression of new technology which will seriously impact how we practice regional anesthesia in the future. The debate about the use of nerve stimulation versus paresthesiae continued for almost 30 years. In today's practice, more than 90% of anesthesiologists use nerve stimulation. However, it did take a long time to convince the artisans of regional anesthesia that the application of nerve stimulation to regional anesthesia had something useful to offer. It seemed that there was some reluctance to abandon the art of regional anesthesia in favor of new technology. Nerve stimulation was the first step in the conversion of regional anesthesia from an art to a science.

One of the most exciting new advances in regional anesthesia in recent years has been the introduction of ultrasound. One of the first reports about the application of ultrasound in regional anesthesia was published in 1989 by Ting and Sivagnanratnam.<sup>5</sup> Since that time, there has been a growing number of reports in the world literature on this exciting application to regional anesthesia. It is only a matter of time before this technology will become mainstream in regional anesthesia. Brachial plexus anesthesia is one of the most challenging techniques in regional anesthesia and ultrasound has great potential to improve our success rate with this technique. When this happens, regional anesthesia will be a true science. The reason that the classic approach

(supraclavicular) did not survive the test of time was that the potential for pneumothorax was an ever-present risk. The application of ultrasound in regional anesthesia may rejuvenate the classic approach to the brachial plexus, because with advances in this technology we will be better able to see the nerve trunks, the blood vessels, the pleura, and the approaching needle. For years we have been blindly inserting needles toward neural targets relying solely on our knowledge of anatomy. The introduction of nerve stimulation has been very helpful in that it provided some objective evidence that our needles were in the vicinity of the target nerve. With ultrasound, we can actually see the neural targets, the vascular structures, the advancing needle in real time, and the actual spread of local anesthetic solution following the injection. This is indeed enormous progress. By combining these two technologies, we can achieve very close to 100% success with these techniques provided we have sufficient time for the local anesthetic to work. There are at least two reports in the literature demonstrating the value of ultrasound techniques for supraclavicular blocks. Koprak et al.<sup>6</sup> demonstrated the safety and efficacy of ultrasound-guided supraclavicular blocks in 20 patients scheduled for upper extremity surgery. More recently, Williams et al.<sup>7</sup> performed ultrasound-guided supraclavicular blocks in 40 patients undergoing upper extremity surgery. They compared the ultrasound technique with nerve stimulation and showed that the ultrasound technique was performed successfully in half the time required to perform the nerve stimulation technique. None of the patients in the ultrasound group required general anesthesia to complete the surgery. We prefer to combine both technologies (ultrasound and nerve stimulation) when performing brachial plexus blocks. Ultrasound allows us to see the advancing needle approach the target nerve or trunk. Nerve stimulation allows one to identify which nerve we are approaching and if indeed it is a nerve. Ultrasound technology is indeed a great advance in regional anesthesia; however, we still have some difficulty accurately identifying structures and the advancing needle is not that easy to see in many cases. A number of regional anesthesia experts practicing ultrasound have already abandoned neurostimulation upon discovering the value of ultrasound. We are not quite ready to do that yet.

In this updated chapter, we will confine our discussion to single-injection, brachial plexus anesthesia in adults. Continuous techniques will be dealt with in Chapter 15.

## General Considerations

Not all patients are suitable candidates for brachial plexus anesthesia. Contraindications to regional anesthesia, regardless of technique, have already been alluded to in many chapters of this text. These include: patient refusal, excessive anxiety, mental illness, infection at the site of injection, clotting abnormalities, gross anatomic distortion, an uncooperative surgeon, an unskilled anesthesiologist, and an unfavorable environment.

Preoperative evaluation should be performed on all patients, preferably in advance of the scheduled surgery in elective cases. Patients should be fasting whenever possible, and brachial plexus anesthesia should not necessarily be chosen to avoid an obvious airway problem or full stomach.

Supraclavicular techniques should be avoided if possible in patients with advanced lung disease because of the risk of ipsilateral phrenic nerve paresis and pneumothorax. Brachial blocks, regardless of approach, should be used cautiously in patients with nerve injury, and, if selected in these circumstances, documentation of the neurologic deficits should be performed before the block.

Patients scheduled for brachial plexus anesthesia should be transported to the operating suite well in advance of the scheduled surgical procedure. Ideally, brachial blocks should be performed in a holding area, to allow ample time for the local anesthetic to work. Even under ideal circumstances, brachial blocks require at least 30

minutes setup time or “soak” time. The moment a patient enters the operating room, the momentum shifts in favor of performing surgery and few surgeons have the patience to wait for a block to work. The anesthesiologist should discuss the site of surgery with the surgeon in advance and select the most appropriate injection site for the procedure (e.g., interscalene for shoulder and upper arm surgery; axillary for elbow, forearm, and hand surgery).

The anesthesiologist should always be accompanied by an assistant when performing brachial plexus anesthesia, because when complications occur, a second pair of hands is essential. The minimal acceptable monitoring while performing brachial plexus anesthesia includes vital signs, electrocardiogram, and pulse oximetry (Chapter 1).

Brachial plexus anesthesia usually requires multiple injections of local anesthetics and most patients benefit from sedation. Sedation, when chosen, should be used judiciously and slowly. Combinations of opioids and benzodiazepines usually suffice. Profound sedation is undesirable because paresthesias may be difficult to discern, the risk of intraneural injection may be increased, and the adequacy of the intervention may be difficult to assess.

One must always be prepared to induce general anesthesia at a moment’s notice while performing brachial plexus anesthesia. Therefore, all the necessary drugs and equipment required should be immediately at hand. It is very important to assess the adequacy of anesthesia before allowing the surgeon to proceed. Absence of pinprick sensation at the site of surgery does not automatically guarantee surgical anesthesia. The most practical way to assess the adequacy of surgical anesthesia is to ask the surgeon to apply the “Allis test” in the geographic area of the incision and then to objectively observe the patient’s reaction. If the patient reacts adversely, one should intervene by asking the surgeon to refrain or to inject local anesthetic at the site of the incision. General anesthesia may be required in some cases. Inadequate surgical anesthesia during regional anesthesia has resulted in litigation.<sup>8</sup> Supplemental peripheral nerve blocks, if necessary, should be performed well in advance of the surgical incision, because they also take time to work.

One should never let one’s ego stand in the way when a block is not working. This is not a time to question the patient’s veracity. If a patient appears to be experiencing pain, do not hesitate to intervene immediately by asking the surgeon to stop operating. Then a decision should be made to infiltrate with local anesthesia or to induce general anesthesia: patient comfort should always be a priority.

There seems to be a subconscious tendency to decrease the level of vigilance over patients undergoing regional anesthesia. Patients undergoing regional anesthesia become hypoxic, hypercarbic, hypertensive, hypotensive, develop arrhythmias, aspirate, and even die; thus, the same degree of vigilance is required as for general anesthesia (Chapter 1).

## **Complications Common to All Approaches to the Brachial Plexus**

### *Local Anesthetic Toxicity*

Local anesthetic toxicity is a recognized complication of major conduction anesthesia. The incidence of toxicity is greater with brachial plexus techniques than most others, because larger than usual doses of local anesthetics are used and the injections are made in and around large vascular channels in the head, neck, and axillary regions. Toxicity occurs most frequently following accidental intravascular injections and rarely following absorption of injected solutions from peripheral sites (Chapter 6). Kozody et al.<sup>9</sup> demonstrated that seizures may occur when doses of bupivacaine as small as 2.5 mg are directly injected into the vertebral artery.

Epidemiologic information about the incidence of local anesthetic toxicity following regional anesthesia is quite sparse. The most up-to-date information comes from

TABLE 8-1. Overall Seizure Rates

Anesthetic	Total no. of procedures	Total no. of seizures	Seizure rate/1000 procedures	95% CI for seizure rate/1000 procedures*
Caudal†	1,295	9	6.9	3.2–13.2
Brachial‡	7,532	15	2.0	1.1–3.3
Axillary	6,620	8	1.2	0.5–2.4
Interscalene	659	5	7.6	2.5–17.7
Supraclavicular	253	2	7.9	1.0–28.6
Epidural§	16,870	2	0.1	0.01–0.4

\*95% CI calculated using Poisson approximation.

†Including only patients  $\geq 18$  years of age.

‡Brachial blocks can be further classified by type: axillary, interscalene, and supraclavicular. The total number of procedures for each type was projected using the 15 seizure procedures and a random sample of 300 nonseizure procedures.

§Excluding epidurals used only for postoperative analgesia.

Auroy et al.<sup>10</sup> who provided us with information on this topic from a large series of patients undergoing regional anesthesia in France. They reported 23 cases of seizures in 103,730 cases. The highest incidence of seizures was observed in patients undergoing peripheral nerve blocks [16/21,278 with a 95% confidence interval (CI) varying between 0.3–4.1]. Brown et al.<sup>11</sup> in the Mayo Clinic published a report focusing on the seizure rate following brachial plexus anesthesia and reported an incidence of 15 seizures in a series of 7532 cases. They also showed that the risk of seizures was at least six times greater with supraclavicular techniques (Table 8-1).

In a much smaller series, Plevak et al.<sup>12</sup> showed that the incidence of seizures following brachial plexus anesthesia was 1.4%.

Clinicians tend to base the dose of local anesthetic required for brachial plexus anesthesia on body weight. There is a poor correlation between weight and plasma levels of local anesthetics following brachial plexus anesthesia (Figure 8-1).<sup>13</sup> Furthermore, age does not seem to influence plasma levels of local anesthetics (Figure 8-2).<sup>14</sup> Winnie et al.<sup>15</sup> have suggested that height is a more useful guide on which to base dose. The size of the upper extremity is probably the most relevant parameter to use;

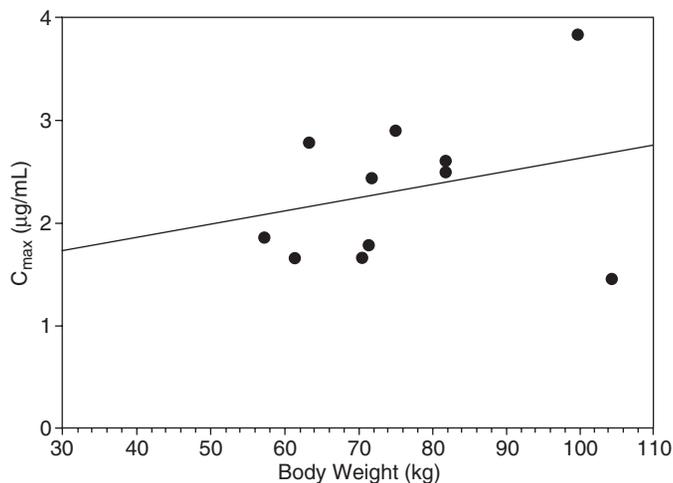
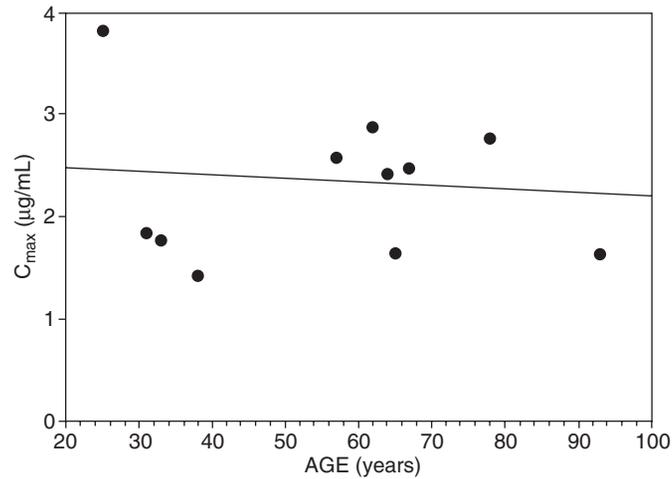


FIGURE 8-1. Correlation between maximum plasma concentration ( $C_{max}$ ) after lidocaine 10mg/kg and body weight.

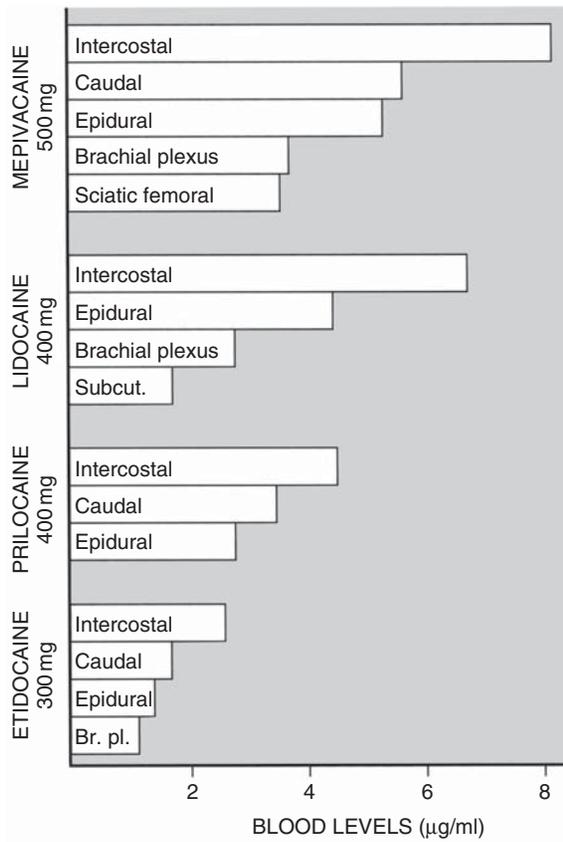


**FIGURE 8-2.** Correlation between  $C_{\max}$  and age after lidocaine.

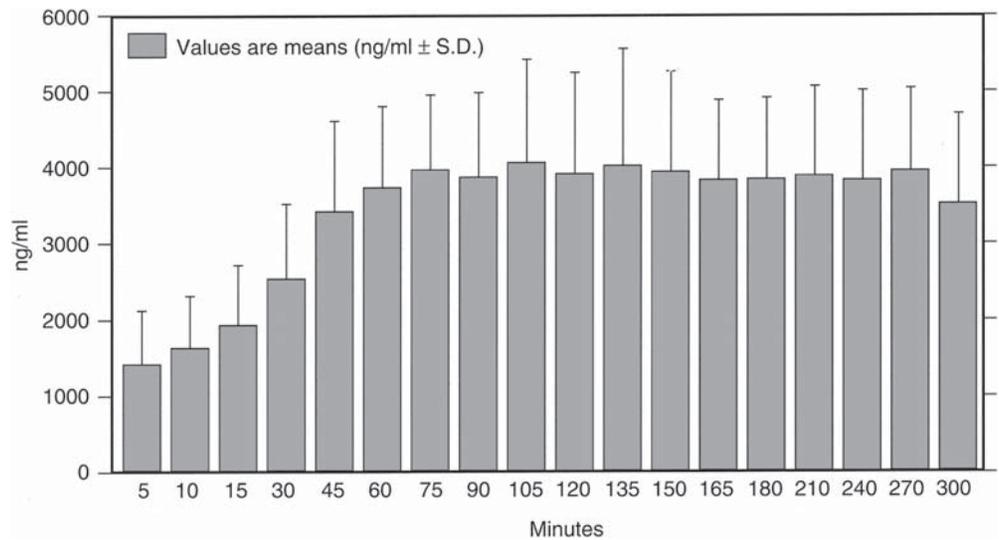
however, it is practically difficult to determine the capacity of the sheath based on the limb size.

The maximum recommended, safe dose of lidocaine for regional anesthesia in adults is 300mg using plain solutions and 500mg for epinephrine-containing solutions.<sup>16</sup> In reality, much larger doses can be safely injected. This topic has been the source of considerable confusion for clinicians for years and the current recommendations about local anesthetic dosage do not have a scientific basis. Rosenberg et al.<sup>17</sup> addressed this topic thoroughly in a recent review. One of the most important factors influencing absorption of local anesthetics from the tissues is the site of injection (Figure 8-3).<sup>18</sup> Absorption of local anesthetics from the brachial plexus sheath is quite slow compared with absorption from the intercostal space. The addition of epinephrine also greatly influences absorption. Cockings et al.<sup>19</sup> showed that 750mg of lidocaine can be safely administered in the axillary region in adults. Finucane and Yilling<sup>20</sup> showed that 750mg of mepivacaine with epinephrine can be safely injected into the axillary region of adults (Figure 8-4). Urmey et al.<sup>21</sup> safely administered 800mg of lidocaine with epinephrine into the interscalene groove. Pälve et al.<sup>22</sup> showed that 900mg of lidocaine with epinephrine was safely administered to patients in the axillary region using the transarterial technique. Plasma levels of local anesthetics were well below those that usually cause symptoms or signs of toxicity in all of these reports. The largest dose of local anesthetic administered for brachial plexus blocks was reported by Büttner et al.<sup>23</sup> who administered approximately 5000mg of mepivacaine to patients in a 24-hour period, during continuous axillary blocks. It should not surprise us that patients tolerate these large doses of local anesthetics, when one considers that cardiologists routinely administer 100-mg boluses of lidocaine followed by up to 250mg per hour intravenously to patients to treat ventricular arrhythmias. Although there is no correlation between plasma level and the weight of patients following a given dose, it is wise to use milligrams/kilogram when dealing with patients who weigh 50kg or less. The obvious question one must ask is why do we need to administer such large dose of local anesthetic drugs for brachial blocks? The reason is that brachial blocks have a very slow onset, especially when injected in the axillary region and when single-injection techniques are used. In summary, larger doses than those traditionally recommended can be safely administered for brachial plexus anesthesia. However, all injections of local anesthetic should be injected slowly and deliberately, with frequent aspirations and observation of the patient, and no more than 5mL of the local anesthetic solution should be administered at any one time.

Caution must be exercised when injecting local anesthetics in patients with liver disease because the ability to metabolize local anesthetics is impaired. The  $t_{1/2}$  alpha



**FIGURE 8-3.** Comparative peak blood levels of several local anesthetic agents after administration into various anatomic sites. (Reprinted from Covino and Vassallo,<sup>18</sup> p 97. Copyright 1976, with permission from Elsevier.)



**FIGURE 8-4.** Mean plasma mepivacaine levels following axillary injection of mepivacaine with epinephrine 10.5mg/kg over a 31-minute period. (From Finucane and Yilling.<sup>20</sup> Copyright 1989, with permission from Lippincott Williams & Wilkins.)

for lidocaine in healthy patients is 1.4 hours after an intravenous injection and increases to 7.3 hours in patients with active hepatitis.<sup>24</sup> Factors that interfere with hepatic blood flow may also influence metabolism of local anesthetics, e.g., age, cardiac failure, and drug therapy (cimetidine and propranolol).<sup>24</sup> The clearance of ropivacaine is reduced by 60% in patients with end-stage liver disease compared with healthy volunteers<sup>25</sup>; despite this, plasma concentrations remain within the normal range. This may be related to an increased volume of distribution at steady state. Alpha<sub>1</sub>-acid glycoprotein (AAG) continues to be synthesized even in the presence of end-stage liver disease. Serious liver disease is often associated with altered renal and cardiac function, which may further impair the pharmacokinetic response of patients. Single-injection techniques, using recommended doses of local anesthetics, are safe in patients with hepatic dysfunction. However, if repeat injections of local anesthetics or continuous techniques are required, the dose of local anesthetics must be significantly reduced (10%–50%) because of a greatly reduced clearance of both the parent product and its metabolites.

Renal function is also an important factor influencing local anesthetic toxicity. The half-life of lidocaine and its primary metabolite, monoethylene glycine xylidine, is not influenced by renal failure. However, the secondary metabolite, glycine xylidine, is heavily dependent on renal function for excretion, and glycine xylidine causes central nervous system toxicity when it accumulates. Gould and Aldrete<sup>26</sup> performed brachial plexus anesthesia in a patient with chronic renal failure on five separate occasions using bupivacaine. They reported bupivacaine toxicity on two occasions out of five. The patient was acidotic and hyperkalemic on both of those occasions. The authors suggested that toxicity occurred because the quantity of free bupivacaine was increased in the presence of acidosis. Other investigators have shown that the concentration of AAG is increased in chronic renal failure and that binding of bupivacaine is increased, resulting in a lower concentration of free bupivacaine and a lower risk of toxicity. Tuominen et al.<sup>27</sup> measured AAG levels in patients with normal renal function following continuous brachial plexus block and showed that they were also increased. Uremic patients frequently have an increased cardiac output which enhances uptake of local anesthetics from the site of action.<sup>28</sup> Studies have shown a rapid uptake of ropivacaine and bupivacaine following brachial plexus anesthesia in uremic patients, and clearance of these compounds and their metabolites is also reduced.<sup>29,30</sup> The dose of local anesthetic should be reduced by 10%–20% in uremic patients even with single-injection techniques, especially when large doses of drugs are usually required. If repeat injections of local anesthetics are required (within 5 half-lives) or continuous techniques are being used, the dose should also be reduced by 10%–20%.

The pharmacokinetics of local anesthetics are also influenced at both extremes of age. However, we will confine our discussion in this chapter to the elderly. A number of changes take place in neural structures as we age. First, blood flow to neural tissue diminishes as we age because of a diminished cardiac output and a progressive decrease in blood flow to all tissues, secondary to arterial disease.<sup>31</sup> Furthermore, axonal function deteriorates and the amount of fat in neural tissue diminishes. There are also some changes in nerve morphology in the elderly<sup>32,33</sup>; consequently, elderly patients are more sensitive to the blocking effects of local anesthetics. The onset of action is faster, duration of neural blockade is prolonged, and clearance is increased. However, plasma levels of local anesthetics, after a single injection, are not increased.<sup>34</sup> For these reasons, the usual doses of local anesthetics are not required in the elderly. If repeat doses or continuous infusions are required, the dose should be reduced by 10%–20% in patients aged 70 years or older.

Occasionally, we are called upon to do a brachial plexus block on a patient who is pregnant. Because larger doses of local anesthetics are required for brachial plexus anesthesia, one should be familiar with the changes in sensitivity to local anesthetics in patients who are pregnant. Progesterone sensitizes the axon to local anesthetics during pregnancy.<sup>35</sup> The uptake of local anesthetics is increased because of increased

cardiac output during late pregnancy.<sup>36</sup> Patients who are pregnant have a reduced degree of protein binding to the longer-acting local anesthetics; therefore, there is more free drug available in the plasma.<sup>37</sup> For all of these reasons, pregnant patients seem to be at greater risk of cardiac toxic effects of the longer-acting local anesthetics. Local anesthetics should be used cautiously during pregnancy. The dose of local anesthetic should be curtailed if possible, even with single-injection techniques. Avoid long-acting agents if large quantities of local anesthetic are required. Epinephrine can be safely added to local anesthetics during pregnancy.<sup>38</sup>

Ropivacaine is the first enantiomerically pure, local anesthetic to be synthesized and was recently approved for clinical use in many countries worldwide. Ropivacaine is similar to bupivacaine in many ways and is less toxic in animals.<sup>39</sup> Ropivacaine has been compared with bupivacaine for brachial plexus anesthesia in double-blind studies and there were no major differences noted.<sup>40</sup> If a long-acting local anesthetic is required, and if large doses or infusions of local anesthetic are being used, it would make good sense to use ropivacaine, because it is less toxic and more rapidly cleared from the circulation.<sup>41</sup>

Ropivacaine has been available for use in regional anesthesia for about 10 years and as expected there have been some sporadic reports of systemic toxic reactions associated with its use. Ropivacaine is not necessarily enhanced by the addition of epinephrine, therefore it is not usually added to this local anesthetic. Ropivacaine is a potent local anesthetic and the addition of epinephrine to it may alert one to the possibility of an unintentional, intravascular injection. Toxic reactions to ropivacaine seem to be no different from those to most local anesthetics and cardiac toxic reactions seem to be easier to treat than those to bupivacaine.<sup>42</sup> Müller et al.<sup>43</sup> reported a grand mal seizure after an accidental intravascular injection of 20 mL of ropivacaine 0.5%. The patient did not exhibit any signs of cardiac toxicity and was readily treated using standard guidelines. Epinephrine was not added to the solution.

In summary, the risk of local anesthesia toxicity is increased following brachial plexus anesthesia and especially following supraclavicular injections. Most toxic reactions result from accidental intravascular injections and can be avoided by slow deliberate injections, of no more than 5 mL of local anesthetic at any one time, with frequent aspirations and careful observation of patients. Epinephrine is a very useful marker for early detection of accidental intravascular injections and is strongly recommended, especially when using potent local anesthetics. Doses much larger than those recommended can be safely administered into the brachial plexus sheath, provided reasonable precautions are taken.

### *Nerve Injury Following Brachial Plexus Anesthesia*

Nerve injury following brachial plexus anesthesia has been a recognized complication since the early days of the technique (Chapter 7).

Kulenkampff<sup>44</sup> advised that in order to avoid injury to the brachial plexus “that ideally only a very fine needle should be used.” In 1954, Bonica,<sup>45</sup> another master of these techniques, made the following statement about nerve injuries: “While it is true that promiscuous, repeated and rough probing of the nerves may cause neurologic sequelae, gently touching the nerve with the needle point does not cause any clinically apparent damage. . . .”

Even after 120 or more years of experience with brachial plexus techniques, we still do not have a good handle on either the incidence of these injuries or, indeed, the mechanism. In a recent report from the Closed Claims Study in the United States, there were 670 claims for nerve injury of a total of 4183 claims.<sup>46</sup> Nerve injuries were the second most frequent injury reported in the Closed Claims Study, accounting for 16% of all injuries going to litigation. Ulnar nerve injury was the most frequent nerve injury following anesthesia and, ironically, the incidence of ulnar nerve injury was far higher following general than regional anesthesia (85%).

Recent data on the incidence of nerve injury following brachial plexus anesthesia are sparse. Auroy et al.<sup>10</sup> published the largest prospective study on nerve injury related to regional anesthesia in recent years. The incidence of serious nerve injury related to peripheral nerve block was quite low. There were only four serious peripheral nerve injuries in a total of 21,278 cases. Two-thirds of the patients who reported serious nerve injuries experienced either paresthesias or pain on injection during the procedure. Plevak et al.<sup>12</sup> reported an incidence of 2.2% in a series of 716 cases and Selander et al.<sup>47</sup> reported an incidence of 1.9% in a series of 533 cases. Löfström and Sjöstrand<sup>48</sup> reviewed the literature on this topic going back to 1949 and showed that the incidence of brachial plexus injury was higher following supraclavicular techniques, and their explanation for this was that the “paresthesia method” was the sole method of verifying accurate needle placement with supraclavicular techniques, whereas paresthesias were not required to verify accurate needle placement in the axillary region. The authors’ suggestion that the paresthesia method may be injurious to nerves sparked considerable controversy, especially among proponents of the paresthesia method, and this topic is still the subject of many debates and the controversy will continue. Moore,<sup>49</sup> who is a well-known master of regional anesthesia techniques, takes credit for the phrase “no paresthesia, no anesthesia,” and has inspired many generations of anesthesiologists to adhere to this dictum. In reality, it is very difficult to prove that the act of deliberately seeking a paresthesia is injurious to nerves. Intuitively, it makes sense that if one encroaches upon a nerve with a cutting needle, the risk of damage increases. The prospective study by Selander et al.<sup>47</sup> failed to demonstrate scientifically that there was an increased incidence of injury following the use of paresthesias. Selander et al.<sup>50</sup> also suggested that the bevel configuration of the needle used influences the incidence and degree of trauma to nerves in both intact and isolated nerve preparations. They demonstrated that sharp-cutting needles are far more injurious to nerves than blunt needles. Rice and McMahon,<sup>51</sup> more than a decade later, challenged Selander et al.’s conclusions, and although they demonstrated a lower overall incidence of nerve trauma after using blunt-beveled needles, they did show that when injuries occurred secondary to blunt-beveled needles, the damage was more serious. This matter is discussed in much greater detail in Chapter 7. We should strive to use the smallest-gauge needle possible when performing local anesthesia techniques, especially when targeting specific nerves. Excessive pressures generated during injections can cause serious damage regardless of the bevel configuration, and we cannot ignore observations in Auroy’s study that paresthesias and pain on injection are harbingers of injury to peripheral nerves. This explains the rationale for avoiding regional anesthesia in anesthetized patients.

Fortunately, most injuries attributable to needle damage cause self-limiting neuropraxias, which resolve in 1–3 months. Serious permanent injuries are rare. One must not assume that all neurologic injuries following regional anesthesia are directly attributable to the anesthetic management. Most serious neurologic injuries are unrelated to anesthetic interventions. Patients occasionally present with covert neurologic injury which only becomes evident in the postoperative period. Nerves are sometimes injured at surgery either accidentally or even deliberately. Improperly applied tourniquets may cause nerve injuries. The incidence of “tourniquet paralysis” has been reported to be as high as 1:8000 procedures.<sup>52</sup> Ideally, the tourniquet pressure should never exceed 150 mm Hg above that of the usual systolic blood pressure and the tourniquet should be deflated within 90–120 minutes if possible. Hidou et al.<sup>53</sup> reported a case of serious tourniquet-related injury after the application of a tourniquet for upper limb surgery for 45 minutes, in a healthy patient. Malposition of the limb during surgery or after surgery may also cause injury. Brachial neuritis<sup>54</sup> is a rare condition that may lead to diagnostic confusion when it occurs in the postoperative period following a brachial block. It is usually preceded by severe pain and is followed by weakness and atrophy of shoulder muscles. Sensory disturbances occur in two-thirds of the cases. The incidence is about 1:100,000. Most cases are preceded by a flu-like illness.

Overall recovery may take up to 2 years. It is most important to take a full history and perform a thorough neurologic examination and request relevant consultation when dealing with nerve injuries. One of the lessons learned from the Closed Claims Study in the United States is that even though appropriate standards of care are met while performing regional anesthesia, plaintiffs' lawyers are very successful in swaying juries to find fault with physicians (Chapter 23). Anesthesia care was judged to be appropriate in 66% of nerve injury cases in the Closed Claims Study.<sup>46</sup>

Forearm and hand surgery is frequently performed on an ambulatory basis. When brachial plexus blocks are performed in these patients, they should be warned about unknowingly injuring the anesthetized limb (e.g., resting the anesthetized limb against a heated radiator or over the back of a chair). They should also be specifically warned about lying on the anesthetized extremity. Ideally, patients should be given written instructions about the inherent dangers of injuring an anesthetized limb following anesthesia and surgery.

Brachial plexus anesthesia should be used with caution in patients with known neurologic damage, especially when the neurologic disease is ongoing.

Löfström and Sjöstrand<sup>48</sup> have shown that deliberate intraneural injection of local anesthetics results in a high incidence of neuropraxia and the injury is not solely the result of needle trauma. Considerable damage may also result from the pressure generated during the injection.

Local anesthetic drugs may also be toxic to nerves. Selander et al.<sup>55</sup> demonstrated in an in vitro study that the incidence of nerve damage increased when epinephrine was added to local anesthetics and the incidence was also influenced by the concentration of the local anesthetic used, especially if the blood/nerve barrier was damaged. This observation has not been demonstrated in clinical practice. Topical application of local anesthetic drugs to nerves (in vitro) does not cause injury, but intrafascicular injection does.

Patients who sustain nerve injuries usually do not develop symptoms immediately and the problem usually becomes evident during the first week postoperatively.

The controversy surrounding the use of paresthesias will continue. There is no proof that deliberate elicitation of paresthesias results in nerve injury. Intuitively, it makes sense to avoid contact with nerves, especially if reliable alternative methods to achieve successful anesthesia exist. If patients experience severe pain on injection, one should stop immediately and reposition the needle. Avoid brachial blocks in comatose patients or in those who cannot communicate. Be very selective about using regional anesthesia in patients with existing neurologic injury or in those in whom neurologic disease is suspected. Avoid concentrated local anesthetics (lidocaine >1.5%). Avoid long needles, and Kulenkampff's<sup>44</sup> advice back in 1928 that, "... ideally only a very fine needle should be used" is as good today as it was more than 75 years ago.

For a more complete discussion on peripheral nerve injury following regional anesthesia, refer to Chapter 7.

### *Failure of Brachial Plexus Anesthesia*

Of all the regional techniques routinely performed, the highest incidence of failure occurs following brachial plexus anesthesia. Failure rates for spinal or epidural anesthesia, in experienced hands, are usually no more than 5%–10%. However, it is not unusual to report failure rates between 20% and 30% with brachial plexus anesthesia. Table 8-2 includes success rates from several series of axillary blocks going back more than 25 years. Although not well documented, it seems that success rates are higher with supraclavicular approaches.

Why are failure rates so high with brachial blocks? There are a number of reasons. Most regional techniques require only a single injection. Single injections of local anesthetic work very well in the supraclavicular region where the nerve trunks are very closely clustered together. In contrast to this, a single injection of local anesthetic

TABLE 8-2. Success Rates with Axillary Brachial Blocks

Author	Year	No.	%
Selander <sup>56</sup>	1977	137	80
Vester-Anderson et al. <sup>57</sup>	1984	240	91
Goldberg et al. <sup>58</sup>	1987	59	76
Cockings et al. <sup>19</sup>	1987	100	99
Baranowski and Pitheer <sup>59</sup>	1990	100	70
Stan <sup>60</sup>	1995	1000	89

into the axilla results in a very slow onset of anesthesia because the nerves are quite separate from one another and perhaps the axillary sheath offers some impediment to uptake by the nerves. It may take up to an hour for the local anesthetic to reach all four major nerves of the upper extremity and may not reach the musculocutaneous nerve at all because that nerve lies outside the axillary sheath in the axilla. We now have the tools to allow us, with much greater certainty, to inject local anesthetic drugs within the sheath. Therefore, we will see fewer and fewer failures attributed to inaccurate placement of local anesthetics. To achieve a rapid onset axillary block, we need to block each individual nerve. Even when local anesthetic drugs are accurately placed, we are limited by the latency of the local anesthetic.

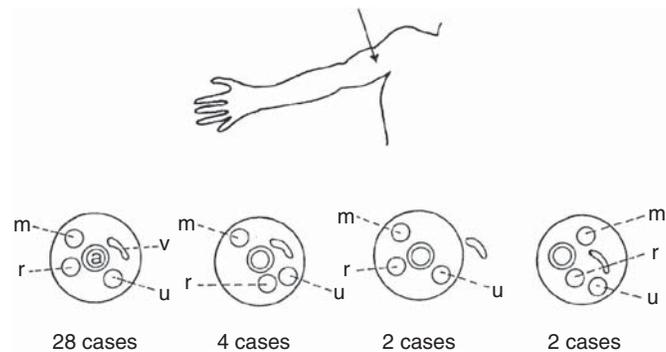
Over the years, a number of different methods have been used to enhance onset of local anesthetics. One of the simplest ways to enhance onset of action of local anesthetics is to increase the quantity of local anesthetic; however, in doing so, we also increase the risk of toxicity and other complications. If we study the intrinsic properties of local anesthetics, we observe that local anesthetic drugs with a low  $pK_a$  and a high lipid solubility have a more rapid onset of action.<sup>18</sup> Etidocaine possesses both of these properties and, therefore, is associated with a very rapid onset of action.

Alkalinization of local anesthetics has been less convincing when used for brachial plexus anesthesia<sup>61-63</sup>; furthermore, there are some disadvantages and risks, e.g., cost, contamination, and the potential for error in preparation.

Carbonation has also been tested with equally equivocal results.<sup>64</sup> Hyaluronidase convincingly enhances onset of retrobulbar blocks, but these positive results have not been seen with brachial blocks.<sup>65,66</sup> Compounding local anesthetics has not added much more benefit than would be achieved by increasing the milligram dose of one or other local anesthetic. One study showed quite a dramatic effect on onset by heating the local anesthetic to 37°C.<sup>67</sup> The onset of action was reduced by about 55% in the major nerves. Cooling local anesthetics<sup>68</sup> has also been recommended and seems to work quite well. However, patients complain of considerable discomfort when cold solutions are injected perineurally (personal communication, B. Tsui, 2005).

Lavoie et al.<sup>69</sup> have shown that the incidence of success is proportional to the number of nerves blocked (using nerve stimulation). One of the most important strategies to use is to selectively block those nerves that provide sensory innervation within the boundaries of the skin incision.

Partridge et al.<sup>70</sup> have provided a very useful diagram showing the distribution of major nerve trunks around the axillary artery (Figure 8-5). From this diagram, one can see that the radial nerve is consistently posterior to the axillary artery, right in the epicenter of the axillary sheath. This favorable position of the radial artery may explain why Stan et al.<sup>60</sup> reported such a high success rate with the transarterial approach. The median nerve is positioned superoposteriorly, and the ulnar nerve inferoanteriorly in most subjects. Therefore, if the intended skin incision encroached on the nerve endings of the median and ulnar nerves, one would selectively block both of these nerves first and, subsequently, block the radial and or musculocutaneous nerve.



**FIGURE 8-5.** Variable anatomy of the axillary sheath. Displayed are drawings of the most common arrangements of components of the neurovascular bundle in 36 dissections from 18 cadavers. Cross-sections were taken at the point labeled with an arrow. Approximate positions of the median (m), radial (r), and ulnar (u) nerves are shown relative to the axillary artery (a) and vein (v). (From Partridge et al.<sup>70</sup> Copyright 1987, with permission from Lippincott Williams & Wilkins.)

The musculocutaneous nerve seems to be quite difficult to block in the axillary region. If the musculocutaneous nerve is the primary target nerve, one may selectively block this nerve high in the axilla, or attempt to block it by injecting directly into the coracobrachialis muscle. Alternatively, Yamamoto et al.<sup>71</sup> have shown a high incidence of musculocutaneous nerve block when the median nerve is the primary target.

The ulnar nerve occasionally eludes the spread of local anesthetic following an interscalene injection. This problem can be circumvented by selectively blocking the ulnar nerve in the axilla as well. This modification of technique is referred to as the axis block.<sup>72</sup>

Single-injection techniques seem to work well in the supraclavicular region but not so in the axillary region, especially if there are time constraints.

Multiple-injection techniques can be achieved using the paresthesia method, nerve stimulation, transarterial method, and just plain infiltration in and around the axillary artery. The multiple-injection technique can be a problem if one relies on nerve stimulation because it is sometimes difficult to elicit a motor response when performing the second or third injection, because the local anesthetic has already spread to adjoining nerves. Bouaziz et al.<sup>73</sup> described a midhumeral approach to the brachial plexus that allows one to readily stimulate all four major nerves, which are widely separated in the midhumeral region.

In summary, brachial plexus anesthesia is associated with a high failure rate. The reasons for failure include: failure to enter the sheath, an inadequate volume and/or milligram dose of local anesthetic, failure to inject the local anesthetic close to the nerve, and perhaps most importantly, an inadequate amount of “soak time.” It is generally agreed that the main limiting factor mitigating against success is time. A number of strategies are recommended, including organizational changes, enhancement techniques, and technical approaches. Single-injection techniques seem to work well in the supraclavicular region and multiple-injection techniques are preferable in the axillary region. Finally, large doses and volumes of local anesthetics are recommended when single-injection techniques are used, especially in the axillary region. Application of some of these strategies should enhance success rates.

Sometimes we become so obsessed with the importance of success in many of life’s pursuits, including regional anesthesia, that we lose sight of the most important issues. The paradigm shift from inpatient to ambulatory surgery has had an enormous impact on the practice of regional anesthesia. The emphasis on “turnover” and “throughput,” the short exposure we have to discuss issues such as regional anesthesia with patients, has had a very negative impact on the practice of regional anesthesia and, especially, brachial plexus anesthesia. We have solved this problem in our

institution by using ultrasound-guided supraclavicular brachial plexus blocks in combination with nerve stimulation. We use combinations of lidocaine 2% and bupivacaine 0.5%. We use combinations of remifentanyl and propofol in large doses initially to facilitate surgery during the early phase while the local anesthetic is penetrating the neural targets. Using this approach, patients are ready for surgery in 20 minutes. We complete five hand surgeries using supraclavicular blocks in a typical day using this approach.

### *Inadvertent Injection of the Wrong Solution*

Inadvertent injection of the wrong solution usually involves intravenous injections. Fortunately, the number of reports of accidental injections of the wrong solution into the brachial plexus sheath are few. Tuohy and MacEvelly<sup>74</sup> described a case in which thiopental was accidentally injected into the axillary sheath. Fifteen milliliters of 2.5% thiopental was injected, after which the patient complained of mild pain. The error was then discovered and an axillary block was performed using 40 mL of lidocaine 1% with adrenaline. Forty milliliters of 0.9% NaCl was also injected into the axillary space to dilute the thiopental. A stellate ganglion block was also performed on the ipsilateral side using bupivacaine 0.25% 15 mL. All regional blocks were successful; however, surgery was postponed. The patient had continuing pain in the axilla on recovery from the blocks, but there were no long-term sequelae.

Patterson and Scanlon<sup>75</sup> reported a case of an inadvertent injection of an antibiotic into the interscalene groove in an 18-year-old male patient. Ironically, the patient was admitted to hospital after traumatic amputation of the left thumb. An interscalene block was performed to improve blood flow and provide postoperative pain relief. A 20-gauge cannula was inserted into the interscalene groove to facilitate additional injections of local anesthetic. When the patient was on the ward, a house officer was called to administer flucloxacillin 500 mg intravenously. He inadvertently injected the antibiotic into the interscalene groove. The patient complained of pain and tingling during the injection, and when the error was discovered, 20 mL of 0.9% NaCl was mixed with 20 mL of bupivacaine 0.25% and injected into the sheath to dilute any remaining antibiotic. There were no long-term sequelae reported. This error was made even though painstaking efforts were taken to prevent such a happening. These cases are sobering reminders that one can never be too careful when administering medications and the presence of a cannula does not automatically mean that the cannula is in a venous channel.

## **Complications of Supraclavicular Techniques**

The potential for serious complications following brachial plexus anesthesia seems to be greater with supraclavicular techniques. A review of the literature reveals that the number of anecdotal reports of complications is greater following supraclavicular techniques even though the axillary approach is used more frequently. The advent of ultrasound should greatly reduce the risk of pneumothorax and increase success rates with this technique.

### *Pneumothorax*

Pneumothorax has been a dreaded complication of supraclavicular techniques since Kulenkempff<sup>4</sup> first described the classic supraclavicular approach in 1911. The risk of pneumothorax has deterred many anesthesiologists from using the supraclavicular approach and is the most likely reason that axillary approaches are more popular. Any technique that requires the insertion of a needle in the direction of the lung carries with it the risk of pneumothorax. Tall, thin patients seem to be at greater risk and the risk is greater on the right side because the cupola of the lung is higher on

the right side. Winnie<sup>76</sup> carefully studied the anatomy of the brachial plexus in the supraclavicular region in the 1970s and noted the intimate relationship the plexus had with the interscalene muscles. As a result of these observations, he popularized the interscalene approach to the brachial plexus. Pneumothorax may occur following the interscalene approach to the brachial plexus; however, the risk is lower than that following the classic supraclavicular approach. Through Winnie's enthusiastic teaching, there has been a renewed interest in supraclavicular techniques during the past 30 years. The true incidence of pneumothorax is difficult to determine and varies to some degree with the approach selected. Brand and Papper<sup>77</sup> reported an incidence of 6.1% in a large teaching hospital using the classic Kulenkampff technique. DeJong<sup>78</sup> found radiologic evidence of pneumothorax in 25% of patients following supraclavicular techniques. The incidence of symptomatic pneumothorax is much less than that. Ward<sup>79</sup> reported a 3% incidence of symptomatic pneumothorax following the interscalene technique. Hickey et al.<sup>80</sup> found no symptomatic pneumothoraces in 156 patients following the subclavian perivascular approach. The majority of upper extremity surgeries are now performed on ambulatory patients who are usually discharged home within a few hours of surgery.

When supraclavicular techniques are used in an ambulatory setting, patients should be warned about the risk of and appraised of the symptoms and signs of pneumothorax. Patients who develop chest pain, dyspnea, or cyanosis after discharge should be instructed to go to the nearest emergency room.

An episode of coughing or sudden inspiratory effort while performing the block may indicate that the pleura has been penetrated and the lung punctured. Symptoms and signs may not develop for hours and patients may not become symptomatic until a 20% pneumothorax is present. A chest tube is usually required when the degree of collapse is 25% or greater. General anesthesia may be required when brachial blocks fail. Positive pressure ventilation with N<sub>2</sub>O/O<sub>2</sub> in the presence of a small pneumothorax may lead to tension pneumothorax with rapid deterioration in vital signs. Therefore, a high index of suspicion should always be present when general anesthesia is required after a failed supraclavicular block, and of course nitrous oxide should always be avoided in these cases.

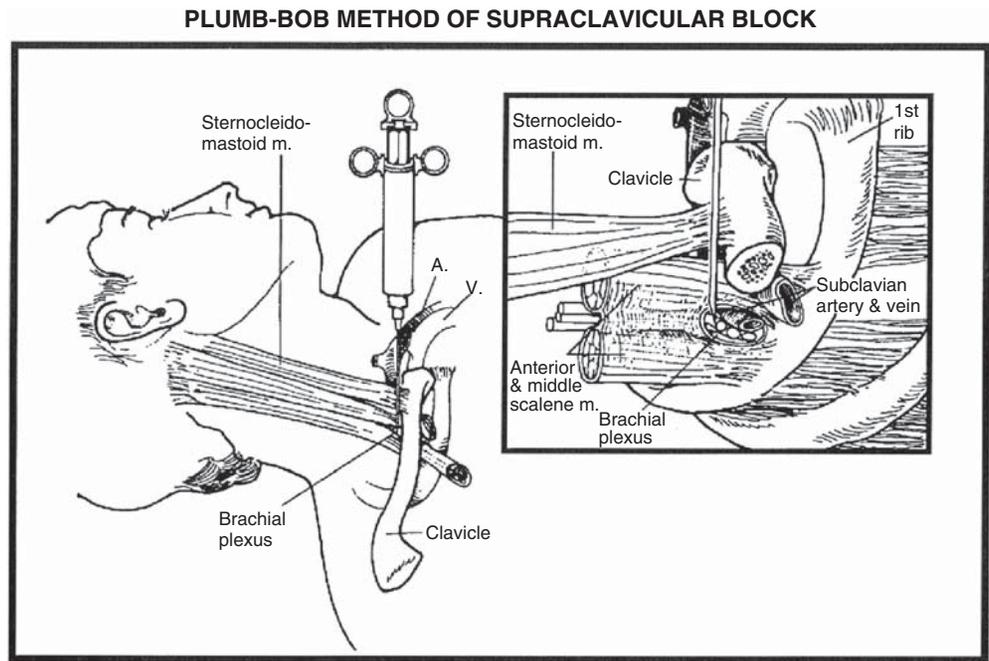
Manara<sup>81</sup> described an unusual case of intrapleural injection of local anesthetic during attempted supraclavicular block. The patient developed anesthesia of the chest wall and eventually upper extremity anesthesia. The patient did not develop symptoms or signs of pneumothorax.

Brown et al.<sup>82</sup> described a new supraclavicular approach entitled the "Plumb-bob" technique (Figure 8-6). The following is a brief description of this technique:

With the patient lying in the supine position, a mark is made on the skin at a point just above where the clavicular head of the sternomastoid meets the clavicle. A needle is inserted at this point in the parasagittal plane with the needle directed at right angles to the plane of the floor. The needle is redirected cephalad in repeated stages until paresthesiae are elicited or until an angle of 30° cephalad is reached. If paresthesiae are not found, the needle is redirected up to 30° in a caudal direction.

Using cadaver, magnetic resonance imaging data, and clinical application in more than 110 patients, Brown has convincingly demonstrated that the "Plumb-bob" method is safe (0% pneumothorax) and effective. Further experiences with this technique in larger numbers of patients will allow us to assess its true value in clinical practice.

In summary, a technique that requires the insertion of a needle in the supraclavicular region, directed toward the lung, carries with it the risk of pneumothorax. Patients should be warned in advance of this risk, and ambulatory patients should be given careful instructions on how to proceed should symptoms develop. Supraclavicular techniques should be used only when indicated. Axillary techniques satisfy the anesthesia demands of most upper extremity surgery, with the exception of the shoulder down to the midhumeral region.



**FIGURE 8-6.** Plumb-bob technique. (From Brown et al.<sup>82</sup> Copyright 1993, with permission from Lippincott Williams & Wilkins.)

### *Phrenic Nerve Paresis*

Ipsilateral phrenic nerve paresis has been reported sporadically since Kulenkampff first described the supraclavicular technique.

In 1979, Knoblanche<sup>83</sup> demonstrated a 67% incidence of ipsilateral phrenic nerve paresis in a small series of patients using an image intensifier following interscalene block. X-rays were taken within 3 hours of supraclavicular brachial plexus block. Knoblanche concluded that the phrenic nerve was blocked peripherally.

In 1981, Farrar et al.<sup>84</sup> demonstrated that the incidence of ipsilateral phrenic nerve paresis varied between 36% and 40% regardless of the supraclavicular technique chosen. This was a retrospective study involving more than 368 cases. X-rays were taken preoperatively and 4 hours after injection of local anesthetic. Farrar et al. concluded that the phrenic nerve was being blocked at the root level as opposed to peripherally.

Urmey et al.<sup>85</sup> studied the incidence of ipsilateral hemidiaphragmatic paresis in 13 patients following interscalene block, using ultrasonography. Data were collected before the block was performed and at 2, 5, 10 minutes and then hourly until normal function was restored. They reported changes in the Sniff and Müller maneuvers within 5 minutes. They also showed that ipsilateral hemidiaphragmatic paralysis occurred in all patients and persisted for 5 hours. Urmey et al. also studied the effect of reducing the mass of local anesthetic on the incidence of phrenic nerve paresis and demonstrated that the incidence was still 100%.

Pere et al.<sup>86</sup> studied the effects of ipsilateral hemidiaphragmatic paralysis on respiratory function in a small series of patients following continuous interscalene block. They demonstrated that all patients had reduced forced vital capacity, forced expiratory volume, and peak expiratory flow. Urmey and McDonald<sup>87</sup> also studied pulmonary function and attempted to quantify the deficit in respiratory function. They corroborated Pere et al.'s findings and showed that forced vital capacity and forced expiratory volume decreased by 27% and 26%, respectively.

Fujimura et al.<sup>88</sup> also evaluated the effects of hemidiaphragmatic paralysis on respiratory function following interscalene block in a small series (10 patients). There

were no major changes in pulmonary function studies; however,  $\text{PaO}_2$  decreased significantly. The clinical significance of this decrease in  $\text{PaO}_2$  was questionable.

We must reevaluate the use of supraclavicular techniques in certain groups of patients in light of this new information. Clearly, supraclavicular techniques should be avoided in patients with advanced pulmonary disease and bilateral supraclavicular techniques are absolutely contraindicated. However, there are anecdotal reports of patients, devoid of respiratory disease, who became symptomatic following interscalene block. Kayerker and Dick<sup>89</sup> described two such cases. The first case was a 42-year-old woman who presented for a right carpal tunnel release. She was healthy apart from mild diabetes. She became symptomatic following interscalene injection of 50 mL of 0.375% bupivacaine. X-ray revealed marked elevation of the hemidiaphragm but no pneumothorax. The second patient was a 39-year-old woman with chronic renal failure scheduled for creation of an arteriovenous fistula. She was also a diabetic. She experienced respiratory difficulty following a similar dose of 0.375% bupivacaine. Neither of these patients required major intervention but were symptomatic for several hours. Hood and Knoblanche<sup>90</sup> also described a case of respiratory distress following a supraclavicular brachial plexus block. This patient also had renal failure and radiologic studies revealed ipsilateral hemidiaphragmatic paralysis and the case was postponed.

Ward<sup>79</sup> described two cases of dyspnea in young patients following interscalene block. Both had radiologic evidence of unilateral phrenic nerve block and were healthy patients aged 19 and 27. The symptoms abated when the block wore off. These two cases represent a 6% incidence of symptomatic phrenic nerve paresis in Ward's series. Rau et al.<sup>91</sup> published a report of significant dyspnea in an obese patient following an interscalene block.

There is, without question, a very high incidence of ipsilateral hemidiaphragmatic paralysis following supraclavicular brachial plexus block, which seems to be of no consequence in the vast majority of healthy patients. These techniques clearly should be avoided in patients with advanced lung disease. Ironically, these were the very cases in whom brachial plexus anesthesia was considered to be safest in the past. The interscalene approach requires the insertion of a needle diagonally toward the sixth cervical nerve root; therefore, one might expect a higher incidence of ipsilateral phrenic nerve paresis when using this technique. One cannot assume that the incidence of this complication is the same with all supraclavicular approaches. Neal et al.<sup>92</sup> studied the incidence of hemidiaphragmatic paresis and respiratory function following supraclavicular blocks in eight healthy volunteers and demonstrated that the overall incidence of paresis was 50% following 30 mL of lidocaine 1.5% with epinephrine. None of these volunteers reported respiratory symptoms. However, until we have more data on this topic, it would be prudent to avoid all supraclavicular techniques in patients with moderate to severe impairment of lung function. There is also some suggestion that the volume and quantity of local anesthetic chosen for supraclavicular blocks may influence the incidence of hemidiaphragmatic paresis. Al-Kaisy et al.<sup>93</sup> performed interscalene blocks on 11 healthy volunteers using either 10 mL of 0.25% or 0.5% bupivacaine. They observed pulmonary function in these volunteers for 90 minutes after the injection of bupivacaine and noted that respiratory function was significantly impaired in the volunteers who received the stronger concentration of bupivacaine. Most of us who perform interscalene blocks for shoulder surgery do so to provide good pain relief in the postoperative period. The duration of action of bupivacaine at any concentration will be significantly curtailed if only 10 mL of solution is used. It would seem that few patients develop symptoms following unilateral hemidiaphragmatic paresis. However, we should inform patients that they may become symptomatic and, of course, it should not be necessary to say this, but bilateral interscalene blocks are never indicated.

In contrast to all of these reports demonstrating the potential negative impact of ipsilateral phrenic nerve paresis on respiratory function, Betts and Eggen<sup>94</sup> reported

a case of unilateral pulmonary edema in a patient who had had an interscalene block for right-sided shoulder surgery. The patient had a combined regional/general technique and developed laryngeal spasm upon emergence. Unilateral pulmonary edema developed on the left side. Negative pressure developed on the left side and did not develop on the right side because diaphragmatic action was impaired on that side.

In summary, ipsilateral phrenic nerve paresis is quite common following all supraclavicular approaches to the brachial plexus. The majority of healthy patients do not experience any symptoms. The duration of action of this impairment depends on the dose and the individual properties of the local anesthetic used. Supraclavicular approaches to the brachial plexus should be avoided in patients with significant lung disease.

### *Neurologic Injury Following Supraclavicular Brachial Plexus Block*

Fortunately, serious neurologic injury following any approach to the brachial plexus is rare. Candido et al.<sup>95</sup> recently reported their experience with neurologic injury following interscalene blocks in a series of 693 patients for shoulder and upper arm surgery. Follow-up was performed in 660 of these patients in 4 weeks. Eighty patients reported neurologic symptoms during the 4-week follow-up period. Symptoms cleared up in 24 of these patients within 48 hours and these were not considered serious symptoms. Thirty-one of these neurologic deficits were linked with the interscalene blocks, including one brachial plexopathy. All the symptoms related to interscalene block resolved spontaneously within 4 weeks except the brachial plexopathy. Independent risk factors for neurologic sequelae related to interscalene block were paresthesias or pain or bruising at the needle insertion site within 24 hours. Surgery performed in the sitting position and bruising at the interscalene block insertion site were considered to be risk factors not related to interscalene block.

Further review of the literature revealed a small number of case reports of neurologic injury following supraclavicular techniques. Barutell et al.<sup>96</sup> described a motor deficit in the distribution of C7, C8, T1 following interscalene brachial plexus block. While performing the block, the patient experienced a sharp paresthesia and marked pain on injection. This warning sign was not heeded, and following an injection of 8mL of local anesthetic, the patient became hoarse and lost consciousness and required intubation. The patient recovered about 1 hour later and the following day had paralysis of the extensor and flexor muscles of her fingers. Subsequent electromyogram revealed total denervation of C8 and T1, with no improvement 2 months later. The authors concluded that the neurologic deficit was caused by needle damage to the roots of C8 and T1. An 8.8-cm needle was used and the clinician failed to heed the warning sign of severe pain on injection. Lim and Pereira<sup>97</sup> described a case of brachial plexus injury following supraclavicular block. It was difficult to determine the etiology of injury in this case. Electromyogram studies revealed that the injury was likely the result of focal demyelination at the level of the cords. The patient recovered after about 8 weeks. A multidose vial of lidocaine 1% combined with 0.1% W/V chlorocresol preservative was used in this case. The patient did experience a paresthesia during the procedure but no major discomfort during injection. The deficit experienced by this patient was predominantly motor. The authors concluded that the deficit was likely attributable to needle or injection trauma.

Bashein et al.<sup>98</sup> described a case of persistent phrenic nerve paresis following interscalene block. Within 30 minutes of a 50-mL injection of bupivacaine 0.5% with epinephrine into the interscalene groove, the patient developed a generalized seizure and subsequently presented with ipsilateral phrenic nerve paresis which did not improve with time. The authors concluded that this injury was likely attributable to needle trauma of the phrenic nerve peripherally. There has been at least one additional report of a case of phrenic nerve paralysis in recent years. Robaux et al.<sup>99</sup> described a case of persistent phrenic nerve paresis following an uneventful interscalene block. The

patient was a 60-year-old man in good general health presenting for shoulder surgery. A Stimuplex HNS 11, short-beveled needle (B. Braun) was used. The phrenic nerve was transiently stimulated during attempts at performing the block. A combination of ropivacaine 0.75% and clonidine was used. The patient recovered uneventfully initially but returned to the hospital 10 days later with shortness of breath. The chest X-ray showed a marked elevation of the hemidiaphragm consistent with paresis of the phrenic nerve. The patient had significant respiratory dysfunction a year later. Electromyography revealed absence of compound action potentials, suggesting that the phrenic nerve was completely interrupted or extensively demyelinated. Although the precise mechanism of injury could not be elucidated on the basis of electromyography, the authors concluded that needle trauma was the likely cause of this injury.

Passannante<sup>100</sup> reported a case of spinal anesthesia and permanent neurologic deficit in a 53-year-old patient following interscalene block for shoulder surgery. The block was performed using a 3-inch insulated needle and the patient was anesthetized when the block was performed. The mechanism of injury is speculative but likely the result of intraneural injection of local anesthetic at the root level. Finally, Winnie et al.<sup>15</sup> described an anecdotal report of a patient who developed a Brown-Séquard syndrome following attempted interscalene block with a spinal needle.

Brockway et al.<sup>101</sup> described a case of prolonged anesthesia following a supraclavicular brachial plexus block. Thirty milliliters of bupivacaine 0.42% was injected using nerve stimulator. The patient did not experience paresthesiae or pain on injection. Full function was restored in 40 hours. It is difficult to explain why the block was so protracted. The likely reason for this protracted block was unusually accurate placement of the local anesthetic.

In summary, permanent neurologic injury is rare following supraclavicular techniques. Lessons to be learned from the cases described above should be heeded:

1. Avoid needles that are more than 1–1/2 inches long.
2. Persistent pain on injection infers intraneural injection and should be a signal to discontinue the injection.
3. Avoid brachial plexus anesthesia in unconscious patients because of their inability to report paresthesias or pain on injection.
4. Avoid high concentrations of local anesthetics.
5. Avoid excessive injection pressures.

#### *Central Neural Blockade Following Supraclavicular Techniques*

Central neural blockade may occur following routine supraclavicular brachial plexus anesthesia. Fortunately, this complication is rare. Winnie et al.<sup>15</sup> suggested three possible mechanisms for this complication. First, the local anesthetic may be directly deposited in the subarachnoid, epidural, or subdural space by advancing a needle toward the central neuraxis. Anatomists have demonstrated that the dural cuff may extend as far as 8 cm beyond the intervertebral foramen. Therefore, it is possible to puncture the dura during a supraclavicular block. Finally, intraneural injection of local anesthetics peripherally move in a retrograde manner and reach the spinal cord and subarachnoid space. Shanta<sup>102</sup> has demonstrated that the epineurium is an extension of the dura and the perineurium an extension of the pia. Rapid onset of spinal anesthesia following attempted supraclavicular block is likely attributable to dural puncture. Slower onset of spinal anesthesia may be explained by retrograde spread of local anesthetics into the substance of the spinal cord, or subperineurial spread. Central neural blockade, although rare, is more likely to occur following interscalene injection of local anesthetics.

Kumar et al.<sup>103</sup> described two cases of epidural block following the interscalene approach to the brachial plexus in 1971. This was one of the first reports of this complication since Winnie's description of the interscalene approach. Dyspnea developed in both patients after about 20 minutes, probably because of bilateral phrenic nerve paresis.

Both patients required assisted ventilation for a period of time and recovered fully within 4 hours. The authors were of the opinion that this complication was likely due to an epidural injection because of the slow onset and maintenance of consciousness.

In 1973, Ross and Scarborough<sup>104</sup> described a case of total spinal anesthesia following an interscalene block in a 16-year-old boy. A 2-inch needle was used. Following a 30-mL injection of local anesthetic, the patient became unconscious and the classic signs of total spinal anesthesia were noted (apnea, papillary dilation, absent corneal reflexes, and hypotension). The patient recovered fully in 2 hours without sequelae. The most likely explanation for this complication was subarachnoid injection of the local anesthetic.

In 1976, Edde and Deutsch<sup>105</sup> described a case of total spinal anesthesia following an interscalene block. Immediately after the needle was withdrawn from the interscalene groove, the patient had a cardiopulmonary arrest with electrocardiogram evidence of ventricular fibrillation. Following resuscitation, it was noted that he had all the signs of total spinal anesthesia. The patient recovered fully without sequelae. The authors used a 6-cm needle and ruled that the most likely cause of the cardiac arrest was total spinal anesthesia.

McGlade<sup>106</sup> described a case of total spinal anesthesia in a 17-year-old male following an interscalene block using 28 mL of lidocaine 1.5% with epinephrine. The patient rapidly became apneic and developed other signs of total spinal anesthesia; however, he rapidly regained his ability to breathe, suggesting the possibility of a subdural injection.

Baraka et al.<sup>107</sup> described a case of total spinal anesthesia following the parascalene approach to the brachial plexus. This patient experienced agonizing pain during the injection, and after 5 mL of local anesthetic was injected, the needle was repositioned. The patient became apneic, hypotensive, and rapidly lost consciousness and had complete relaxation of the masseter muscles and vocal cords. The authors attributed these symptoms to an intraneural injection of local anesthetic with central spread to the subarachnoid space.

Dutton and Eckhardt<sup>108</sup> report a case of total spinal anesthesia in a 30-year-old patient following an interscalene block. A 2.5-cm, short-beveled, 22-gauge needle was used. A total of 40 mL of a mixture of bupivacaine 0.5% and lidocaine 2% was used. The patient moved suddenly after a significant portion of the local anesthetic was injected and the remainder of the injection was completed. The patient rapidly became apneic and unresponsive and was immediately intubated. The cardiovascular system remained relatively stable during this episode. Spontaneous breathing resumed in 2 hours following with the patient was extubated but reintubation was required because of further respiratory embarrassment. The patient recovered soon thereafter without permanent sequelae.

The symptoms and signs reported in this case were very typical of those occurring following a subarachnoid injection. It is likely that the needle entered the subarachnoid space when the patient moved suddenly.

Norris et al.<sup>109</sup> reported a case of delayed onset spinal anesthesia following interscalene brachial plexus blockade. These authors did not provide details about the length of needle used for the block but did mention that forearm paresthesias were obtained at a depth of 2 cm. They then proceeded to slowly inject 30 mL of a mixture of bupivacaine 0.5% and carbonated lidocaine 2%. During the initial injection, they reported a paresthesia in the contralateral arm which they attributed to cycling of the blood pressure cuff. A dense block of the upper extremity ensued. A surgical incision over the radial head was performed 12 minutes after the injection. Upon completion of surgery 50 minutes later, the patient moved herself onto the stretcher. Sixty-five minutes after the initial injection, the patient experienced weakness in the contralateral arm and had difficulty moving her head. Examination at that time revealed a dense bilateral motor and sensory block extending from C2 to T4. Her vital signs were stable and she had no difficulty breathing. The block gradually extended to the lumbar

region after 110 minutes. The block regressed to the cervicothoracic dermatomes after 4 hours and 20 minutes, during which time the patient was completely stable. The patient was admitted for observation overnight and was discharged the following morning. She was readmitted 40 hours later because of a severe postdural puncture headache. She was discharged 3 days later and had no further sequelae. It is quite difficult to explain what happened in this case. The contralateral paresthesia observed at the initial injection obviously was significant in retrospect, but if indeed the needle was in the subarachnoid space, the subsequent injection of the 30 mL of local anesthetic would have resulted in a total spinal. Perhaps the needle was repositioned after the initial paresthesia was reported and only a very small quantity of local was injected into the subarachnoid space. Patients are usually quite heavily sedated during regional anesthesia and therefore the extent of the block may not have been fully observed until the patient was asked to move upon completion of the procedure.

Majid et al.<sup>110</sup> reported a case of total spinal anesthesia following a posterior approach to the brachial plexus. They used a 100-mm, 21-gauge Stimuplex, short-beveled needle (B. Braun). Following an injection of 18 mL of 0.5 % bupivacaine, the patient developed a rapid, flaccid paralysis of all extremities and became apneic yet remained conscious and he had a moderate decrease in blood pressure (80/40 mm Hg). The patient was anesthetized and the procedure was completed. Following a 2-hour procedure, the patient awoke and was able to breathe spontaneously. This was another example of an excessively long needle being used. It is likely that the needle deviated toward the central neuraxis, and judging by the rapidity of the symptoms and signs, the needle must have entered the subarachnoid space.

There have been several other cases of bilateral cervical and thoracic anesthesia following interscalene block that do not fit the typical description of epidural injections. Some of these cases present only with sensory anesthesia, others with varying degrees of motor and sensory anesthesia. The most likely explanation for these atypical cases is seepage of local anesthetic into the epidural space following interscalene block.

Anesthesiologists performing this technique should be aware of the potential for subarachnoid, subdural, epidural, intraneural, or intravascular injection. The length of the needle used for interscalene block should not usually exceed 3.8 cm (1.5 inches) and the needle should never be introduced perpendicularly toward the central neuraxis. Difficult injection and persistent painful ipsilateral or contralateral paresthesiae may indicate that the needle is in the central neuraxis, and if there is any doubt about needle placement it should be repositioned before injecting local anesthetic. Both the volume and concentration of local anesthetics may influence the incidence of this complication. Volumes of local anesthetic in excess of 30 mL have been used in most cases of abnormal spread following interscalene block. Interscalene blocks are in effect paravertebral blocks and we are aware that spread into the adjoining epidural space occurs in 80% of cases. Concentrations of local anesthetic greater than 1.5% lidocaine or its equivalent should also be avoided. Finally, interscalene blocks and indeed all brachial blocks should be avoided in unconscious patients, if possible.

Upon reading a series of case reports of central neural spread of local anesthetics following attempted interscalene block, one may get the impression that this is a common occurrence. The senior author of the chapter has not observed one case of total spinal anesthesia following an interscalene block in 35 years of practice in teaching hospitals; therefore, this is not a common occurrence. However, one must always be prepared to deal with this emergency should it occur.

### *Horner's Syndrome*

Horner's syndrome is a common accompaniment of all supraclavicular approaches to the brachial plexus. It is difficult to label it as a complication because it is quite harmless other than causing unilateral nasal stuffiness. Uninformed enthusiastic clinicians

may diagnose “red eye” in patients following supraclavicular block. Occasionally, patients with blunt head trauma present with upper extremity injuries. Regional anesthesia is often a good option in these patients. Horner’s syndrome may present some diagnostic dilemmas in some of these cases; therefore, supraclavicular techniques should be avoided for this reason.<sup>111</sup> The incidence of Horner’s syndrome varies considerably (18.5%–98%)<sup>80</sup> and is no indication of the success or failure of a block. Patients should be informed of this side effect because it is associated with some temporary distortion of the facies.

Sukhani et al.<sup>112</sup> reported a case of persistent Horner’s syndrome following an interscalene block. The patient was a middle-aged woman who was concerned about the distortion in her appearance, especially the ptosis, and requested treatment. The patient was initially treated with neosynephrine drops which proved unsatisfactory and surgery was recommended. The patient declined surgery and her condition improved with time. Fortunately, this is a rare complication.

### *Recurrent Laryngeal Nerve Palsy*

Hoarseness is an occasional complication of interscalene and subclavian perivascular techniques, and is most likely caused by ipsilateral recurrent laryngeal nerve block. Ward<sup>79</sup> reported an incidence of 3% and Ramamurthy<sup>80</sup> an incidence of 1.5%. This complication is usually of little consequence other than an annoyance to patients, but again is a reminder to avoid bilateral interscalene blocks.

Rollins et al.<sup>113</sup> reported an unusual case of airway obstruction following a subclavian perivascular block. The patient was a 71-year-old woman with squamous cell carcinoma of the tongue presenting for a right-sided open reduction and internal fixation of a fractured humerus. She had had a previous neck dissection and partial glossectomy on the left side. She had a difficult airway for other reasons also. The plan was to perform a subclavian perivascular block followed by a fiberoptic-assisted intubation. The patient developed respiratory difficulties shortly after the block was performed. It was subsequently noted that the patient had left vocal cord paresis before the performance of the block. The likely cause of the airway difficulty was a right-sided recurrent laryngeal nerve block which in addition to a left-sided recurrent laryngeal paresis led to complete airway obstruction. Plit et al.<sup>114</sup> reported a very similar case in which an elderly patient presented for shoulder arthroplasty. She had had a thyroidectomy 35 years previously for carcinoma. The patient developed hoarseness and respiratory obstruction following an interscalene block and subsequently required a tracheostomy. These two cases illustrate the danger of supraclavicular blocks in patients who have had major neck surgery in the past.

### *Bronchospasm*

There have been some isolated cases of bronchospasm following interscalene block. The mechanism is not well understood. Thiagarajah et al.<sup>115</sup> suggested that blockade of the sympathetics to the bronchi may cause bronchospasm because of unopposed action of the parasympathetics. However, this explanation Shah and Hirschman<sup>116</sup> pointed out that the lungs are sparsely innervated by sympathetic nerves and if bronchospasm was caused by this mechanism, unilateral bronchospasm would occur. Bronchospasm occurs occasionally following spinal and epidural anesthesia also, and although the mechanism of bronchospasm is not well understood, one should be aware of this complication in patients who have asthma.

### *Other Complications of Supraclavicular Techniques*

Hematoma formation occasionally occurs following supraclavicular techniques and is usually of no consequence. Ramamurthy<sup>80</sup> reported a 22% incidence of subclavian puncture and a recognizable hematoma in 1.4% of cases. Ward<sup>79</sup> reported a 3%

incidence in a series of 34 cases and Brand and Papper<sup>77</sup> reported a 1.2% incidence in a series of 230 cases.

Durrani and Winnie<sup>117</sup> reported a case of “locked in syndrome” following a probable intraarterial injection of local anesthetic following an interscalene block.

Mani et al.<sup>118</sup> reported an unusual case of bleeding and hemopneumothorax in a patient who was heparinized following an otherwise uneventful subclavian perivascular block.

Siler et al.<sup>119</sup> reported an unusual case of carotid bruit following an interscalene block which dissipated within a few hours of the block. It was suggested that injection of the local anesthetic encroached upon the lumen of the carotid artery during performance of the block. There were no permanent sequelae.

#### *Auditory Impairment Associated with Interscalene Block*

Rosenberg et al.<sup>120</sup> described a case of ipsilateral deafness in a 24-year-old patient during continuous interscalene block. Rosenberg subsequently performed audiometry on 20 patients following interscalene block. Three patients reported hearing impairment on the day of surgery which was restored the following day. Sympathetic blockade may have been implicated, although patients in the series with Horner’s syndrome did not have hearing impairment.

In summary, the risk of complications following supraclavicular approaches to the brachial plexus is clearly not rare. The majority of these complications have a direct impact on pulmonary function. For this reason, supraclavicular techniques should be avoided in patients with significant impairment of pulmonary function. The risk of central neural blockade seems to be higher following the interscalene approach. Long, large-gauge needles should be avoided. Volumes of local anesthetic should not exceed 40 mL and concentrations greater than 1.5% lidocaine or its equivalent should be avoided. The needle should be repositioned if significant pain is experienced on injection, and for this reason, these techniques should be avoided in comatose patients.

### **Complications Following the Axillary Approach to the Brachial Plexus**

The axillary approach to the brachial plexus continues to be the most popular technique selected by anesthesiologists for forearm and hand surgery. Axillary blocks are also very effective for elbow surgery,<sup>121</sup> but this fact was only recently realized. The main reasons that the axillary approach is so popular are that it is easy to perform, easy to teach, and the risk of complications is lower than the supraclavicular approach. However, the axillary approach is not devoid of complications. In common with supraclavicular techniques, local anesthetic toxicity, nerve injury, and failure are the most common complications. There are also some very specific complications unique to the axillary approach.

#### *Vascular Complications*

The axillary artery is the main landmark used by anesthesiologists to identify the nerves of the axillary plexus and, as such, may be accidentally or deliberately penetrated. The transarterial approach to the axillary plexus is considered to be one of the most reliable methods with a very high success rate. The transarterial method is now accepted as a standard method of inducing successful axillary block. However, there are some risks associated with this technique. The technique requires penetration of the artery at two points; therefore, the risk of hematoma formation is real. There are a few anecdotal reports of loss of circulation to the upper extremity following the transarterial approach. The pulse usually returns when the sympathetic block sets in. Merrill et al.<sup>122</sup> described a similar case of temporary vascular insufficiency in

TABLE 8-3. Complications Following Transarterial Axillary Block

Complication	No.	%	N
Vascular spasm	10	1	1000
Hematoma	2	0.2	1000
Systemic toxicity	2	0.2	1000
Persistent paresthesia	2	0.2	1000

a 49-year-old patient undergoing hand surgery. The authors concluded that vasospasm was the most likely cause of the problem. The most up-to-date information about the transarterial approach comes from Stan et al.<sup>60</sup>, who published their experience with this technique in 1000 consecutive cases. They reported a successful block in 88.8% of patients. Ten percent required supplementation and only 1.2 required general anesthesia. The incidence of complications was very low (Table 8-3). This is the largest published series of cases performed using the transarterial approach and offers strong support to the safety of this interesting approach to axillary blocks.

In 1984, Restelli et al.<sup>123</sup> described a more serious problem of insufficient venous drainage following a routine axillary block. The transarterial approach was not used in this case but instead the paresthesia method was used. The patient returned a month later with severe pain and swelling in the arm and hand. Surgical exploration of the axilla revealed an aneurysm of the axillary vein which was repaired with good results. This complication was most likely caused by subadventitial injection with subsequent hematoma and aneurysm of the vein wall.

Ott et al.<sup>124</sup> described a serious case of vascular insufficiency following a routine axillary block. The patient was an obese 16-year-old who had an uneventful surgery, but returned 2 weeks later with vascular insufficiency and an 8-cm thrombus was removed from the axillary artery following arteriotomy. A saphenous vein graft was required to repair the artery. One should emphasize that the transarterial approach was not used in this case.

Radiologists perform percutaneous angiography using the axillary artery and have reported nerve injury following hematoma formation and they stressed the importance of prompt surgical exploration when neural deficits occur. This may not be much consolation to the anesthesiologist who must wait until motor and sensory function returns after a block.<sup>125</sup> It is likely that radiologists use much larger needles and multiple punctures, thus hematoma formation is more common. Despite the very high success rates and low complication rate reported with the transarterial approach, deliberate penetration of the axillary artery at two points is not without risk. However, serious complications have been reported in the absence of arterial violation. Blunt needles may be more damaging to blood vessels than sharp ones. Perhaps the best advice is to use fine-caliber needles whenever possible.

## Conclusion

This is an attempt to provide a comprehensive review of complications following brachial plexus anesthesia reported during the past 30 years or so. Although the overall incidence of complications following brachial plexus anesthesia is low, the proportion of complications following supraclavicular methods is much higher than that reported following axillary blocks; e.g., the incidence of seizure activity following interscalene or subclavian perivascular methods is at least six times that of the axillary approach.

Many of the complications of supraclavicular methods have an impact on pulmonary function; therefore, supraclavicular methods should be avoided in patients with even moderate pulmonary dysfunction. In a sense, there should always be a clear-cut

indication for selecting supraclavicular methods because of the risk of pulmonary complications. The incidence of neurologic complications is higher following supraclavicular approaches.

Most of the serious complications of brachial plexus anesthesia are avoidable. Local anesthetic drugs must be injected slowly and patients must be observed carefully for signs of local anesthetic toxicity. The addition of epinephrine to local anesthetics is a useful marker for detecting accidental intravascular injections.

Persistent pain on injection of local anesthetics is a clear warning of an intraneural injection. Large-gauge and long needles should be avoided and brachial blocks should be avoided in comatose patients.

Finally, brachial plexus anesthesia is not yet an exact science. Ultrasound-guided needle insertion is rapidly converting regional anesthesia from an art to a science. There has been renewed interest in regional anesthesia as a result of this great advance. Brachial plexus block has been a great challenge to anesthesiologists for more than 100 years. We can expect success rates close to 100% in the near future. However, complications will still occur. We must select patients carefully. We must seek informed consent. We must select the safest approach. We must use an appropriate dose of local anesthetic. We must minimize patient discomfort and we must know when to abandon our efforts when we are not being successful.

## References

1. Köller C. History of cocaine as a local anesthetic. *JAMA* 1941;117:1284–1285.
2. Halsted WS. Surgical papers. In: Burket WC, ed. 1st ed. Baltimore: Johns Hopkins Press; 1925.
3. Hirschel G. Anesthesierung des plexus brachialis bei operationen an der oberen extremität. *Muenchener Medizinische Wochenschrift* 1911;58:1555–1556.
4. Kulenkampff D. Anesthesia of the brachial plexus [German]. *Zentralb Chir* 1911; 38:1337–1340.
5. Ting PL, Sivagnanratnam V. Ultrasonographic study of the spread of local anesthetic during axillary brachial plexus block. *Br J Anaesth* 1989;63:326–329.
6. Koprál S, Krafft P, Eibenberger K, et al. Ultrasound-guided supraclavicular approach for regional anesthesia of the brachial plexus. *Anesth Analg* 1994;78:503–507.
7. Williams SR, Chouinard P, Arcind G, et al. Ultrasound guidance speeds execution and improves quality of supraclavicular block. *Anesth Analg* 2003;97:1518–1523.
8. Kroll DA, Caplan RA, Posner K. Nerve injury associated with anaesthesia. *Anaesthesiology* 1990;73:202–207.
9. Kozody B, Ready LB, Barsa JE, et al. Dose requirement of local anaesthetic to produce grand mal seizure during stellate ganglion block. *Can Anaesth Soc J* 1982;29:489–491.
10. Auroy Y, Narchi P, Messiah A, et al. Serious complications related to regional anesthesia: results of a prospective survey in France. *Anesthesiology* 1997;87:479–486.
11. Brown DL, Ransom DM, Hall JA, et al. Regional anaesthesia and local anesthetic – induced systemic toxicity: seizure frequency and accompanying cardiovascular changes. *Anesth Analg* 1995;81:321–328.
12. Plevak DJ, Lindstromberg JW, Danielson DR. Paresthesia vs non-paresthesia – the axillary block [abstract]. *Anesthesiology* 1983;59:A216.
13. Finucane BT, Zaman N, Kashkari I, et al. The dose of lidocaine selected for axillary blocks should not be based on body weight in adults [abstract]. *Can J Anaesth* 1998:A 47B.
14. Finucane BT, Zaman N, Tawfik S, et al. Influence of age on the uptake of lidocaine from the axillary space [abstract]. 4th American-Japanese Congress. San Francisco; 1997.
15. Winnie AP, Hakansson L, Buckhoj P. *Plexus Anaesthesia Perivascular Techniques of Brachial Plexus Block*. Philadelphia: WB Saunders; 1983.
16. Canadian Pharmaceutical Association. *Compendium of Pharmaceuticals and Specialties CPS*. 29th ed. Toronto; 1994.
17. Rosenberg PH, Veering PD, Urmey WF. Maximum recommended doses of local anesthetics: a multifactorial concept. *Reg Anesth Pain Med* 2004;29:564–575.

18. Covino BG, Vassallo HG. *Local Anesthetics: Mechanisms of Action and Clinical Use*. New York: Grune & Stratton; 1976.
19. Cockings E, Moore PL, Lewis RC. Transarterial brachial plexus blockade using high doses of 1.5% mepivacaine. *Reg Anesth* 1987;12:159–164.
20. Finucane BT, Yilling F. Safety of supplementing axillary brachial plexus blocks. *Anesthesiology* 1989;70:401–403.
21. Urmev WF, Stanton J, Sharrock NE. Interscalene block. Effects of dose volume and mepivacaine concentrations on anesthesia and plasma levels [abstract]. *Reg Anesth* 1994;19:34.
22. Pälve H, Kirvela O, Olin H, et al. Maximum recommended doses of lidocaine are not toxic. *Br J Anaesth* 1995;74:704–705.
23. Büttner J, Klose R, Argo A. Serum levels of mepivacaine – HCl during continuous axillary plexus block: a prospective evaluation of 1,133 cases. *Reg Anesth* 1989;14:124–127.
24. Covino BG, Scott DB. *Handbook of Epidural Anesthesia and Analgesia*. New York: Grune & Stratton; 1985.
25. Jokinen M. Effects of drug interactions and liver disease on the pharmacokinetics of ropivacaine [PhD thesis]. University of Helsinki, Finland; 2003.
26. Gould DB, Aldrete JA. Bupivacaine cardiotoxicity in a patient with renal failure. *Acta Anaesthesiol Scand* 1983;27:18–21.
27. Tuominen M, Haasio J, Hekali R, et al. Continuous interscalene brachial plexus block. Clinical efficacy, technical problems and bupivacaine plasma concentration. *Acta Anaesthesiol Scand* 1989;33:84–88.
28. Norio K, Mäkisalo H, Isonemi H, et al. Are diabetic patients in danger at renal transplantation? An invasive perioperative study. *Eur J Anaesthesiol* 2000;17:729–736.
29. Pere P, Salonen M, Jokinen M, et al. Pharmacokinetics of ropivacaine in uremic and non-uremic patients after axillary brachial plexus block. *Anesth Analg* 2002;96:563–569.
30. Wald-Oboussier G, Viell B, Biscopig J, et al. Die Wirkung von Bupivacain-HCL nach Supraklavikulärer Plexusblockade bei Patienten mit chronischer Niereninsuffizienz. *Reg Anesth* 1988;11:65–70.
31. Bowdle TA, Freund PR, Slattey JT. Age-dependent lidocaine pharmacokinetics during lumbar peridural anesthesia with lidocaine hydrocarbonate and lidocaine hydrochloride. *Reg Anaesth* 1986;11:123–127.
32. Kurokawa K, Mimori Y, Tanaka E, et al. Age-related change in peripheral nerve conduction: compound action potential duration and dispersion. *Gerontology* 1999;45:168–173.
33. Igarashi T, Hirabayashi Y, Shimizu R, et al. The lumbar extradural structure changes with increasing age. *Br J Anaesth* 1997;78:149–152.
34. Finucane BT, Hammonds WD, Welch MB. Influence of age on the vascular absorption of lidocaine from the epidural space. *Anesth Analg* 1987;66:843–846.
35. Butterworth JF, Walker FO, Lysak SZ. Pregnancy increases median nerve susceptibility to lidocaine. *Anesthesiology* 1990;72:962–965.
36. Pihlajamäki K, Kanto J, Lindberg R, et al. Extradural administration of bupivacaine: pharmacokinetics and metabolism in pregnant and non-pregnant women. *Br J Anaesth* 1990;64:556–562.
37. Santos AC, Pederson H, Harmon TW, et al. Does pregnancy alter the systemic toxicity of local anesthetics? *Anesthesiology* 1989;70:991–995.
38. Brownridge P, Cohen SE, Ward ME. Neural blockade for obstetric and gynecologic surgery. In: Cousins MJ, Bridenbough PO, eds. *Neural Blockade in Clinical Anesthesia and Management of Pain*. Philadelphia: Lippincott-Raven; 1988:557–604.
39. Markham A, Faulds D. Ropivacaine. A review of its pharmacology and therapeutic use in regional anaesthesia. *Drugs* 1996;52:429–438.
40. Hickey R, Hoffman J, Ramamurthy S. A comparison of ropivacaine 0.5% and bupivacaine 0.5% for brachial plexus block. *Anesthesiology* 1991;74:639–642.
41. Lee A, Fagan D, Lamont M, et al. Disposition kinetics of ropivacaine in humans. *Anesth Analg* 1989;69:736–739.
42. Finucane BT. Ropivacaine cardiac toxicity – not as troublesome as bupivacaine. *Can J Anaesth* 2005;52:449–453.
43. Müller M, Litz RJ, Hubler M, Albrecht DM. Grand mal convulsion and plasma concentrations after intravascular injection of ropivacaine for axillary brachial plexus blockade. *Br J Anaesth* 2001;87:784–787.

44. Kulenkampff D. Brachial plexus anaesthesia: its indications, techniques and dangers. *Ann Surg* 1928;87:883–888.
45. Bonica JJ. *The Management of Pain*. 2nd ed. Philadelphia: Lea & Fabinger; 1954.
46. Cheney FW, Domino KB, Caplan RA, et al. Nerve injury associated with anaesthesia: a closed claims analysis. *Anesthesiology* 1999;90:1062–1069.
47. Selander D, Edshage S, Wolff T. Paresthesia or no paresthesia. *Acta Anaesthesiol Scand* 1979;23:27–33.
48. Löfström JB, Sjöstrand U. *Local Anesthesia and Regional Blockade*. Amsterdam: Elsevier; 1988.
49. Moore DC. *Regional Block*. 4th ed. Springfield, IL: Charles C. Thomas; 1975.
50. Selander D, Dhuner KG, Lundsberg G. Peripheral nerve injury due to injection needles used for regional anaesthesia. *Acta Anaesthesiol Scand* 1977;21:182–188.
51. Rice ASC, McMahon SB. Peripheral nerve injury caused by injection needles used in regional anaesthesia: influence of bevel configuration studied in a rat model. *Br J Anaesth* 1992;69:433–438.
52. Middleton RW, Varian JP. Tourniquet paralysis. *Aust NZ J Surg* 1974;44:124–128.
53. Hidou M, Huraux C, Viry-Babel F, et al. Pneumatic tourniquet paralysis: a differential diagnosis after loco-regional anaesthesia of the upper limb. *J Chir* 1992;129:213–214.
54. Fibuch EE, Mertz J, Geller B. Postoperative onset of idiopathic brachial neuritis. *Anesthesiology* 1996;84:455–457.
55. Selander D, Brattsand R, Lungborg G, et al. Local anaesthetics: importance of mode of application, concentration and adrenaline for the appearance of nerve lesions. *Acta Anaesthesiol Scand* 1979;23:127–136.
56. Selander D. Axillary plexus block, paresthetic or perivascular. *Anesthesiology* 1987;66:726–728.
57. Vester-Andersen T, Husum B, Lindeburg T, Borrits L, Gothgen I. Perivascular axillary block IV: blockade following 40, 50 or 60 ml of mepivacaine 1% with adrenaline. *Acta Anaesthesiol Scand* 1984;28:99–105.
58. Goldberg ME, Gregg C, Larijani GE, et al. A comparison of three methods of axillary approach to the brachial plexus block for upper extremity surgery. *Anesthesiology* 1987;66:814–816.
59. Baranowski AP, Pitheer CE. A comparison of three methods of axillary brachial plexus anaesthesia. *Anaesthesia* 1990;45:362–365.
60. Stan T, Krantz MA, Soloman DL, et al. The incidence of neurovascular complications following axillary brachial plexus block, using a transarterial approach. *Reg Anesth* 1995;20:486–492.
61. Difazio CA, Carron H, Grosslight KA, et al. Comparison of pH adjusted lidocaine solutions for epidural anaesthesia. *Anesth Analg* 1986;65:760–763.
62. Hilgier M. Alkalinization of bupivacaine for brachial plexus block. *Reg Anesth* 1985;10:59–61.
63. Morison DH. Alkalinization of local anaesthetics. *Can J Anaesth* 1995;42:1076–1078.
64. McClure JH, Scott DB. Comparison of bupivacaine HCL and carbonated bupivacaine in brachial plexus block by the interscalene technique. *Br J Anaesth* 1981;53:523–526.
65. Keeler JF, Simpson JH, Ellis FR. Effect of addition of hyaluronidase to bupivacaine during axillary brachial plexus block. *Br J Anaesth* 1992;68:68–73.
66. Rosenquist RW, Berman S, Finucane BT. Hyaluronidase and axillary brachial plexus block: effect on latency and plasma levels of local anaesthetics [abstract]. *Reg Anesth* 1989;14:50.
67. Heath PJ, Brownlee GS, Herrick MJ. Latency of brachial plexus block. *Anaesthesia* 1990;40:297–301.
68. Butterworth JF, Walker FO, Neal JM. Cooling potentiates lidocaine inhibition of median nerve sensory fibers. *Anesth Analg* 1990;70:507–511.
69. Lavoie J, Marlin R, Tetrault JP. Axillary plexus block using a peripheral nerve stimulator: single or multiple injections. *Can J Anaesth* 1992;39:583–587.
70. Partridge BL, Katz J, Beninschke K. Functional anatomy of the brachial plexus sheath: implications for anaesthesia. *Anesthesiology* 1987;66:743–747.
71. Yamamoto K, Tsubokawa T, Shibata K, Kobayashi T. Area of paresthesia as determinant of sensory block in axillary brachial plexus block. *Reg Anesth* 1995;20:493–497.
72. Urmey WF. Combined axillary–interscalene (axis) brachial plexus block for elbow surgery [abstract]. *Reg Anesth* 1993;18:88.

73. Bouaziz H, Narchi P, Mercier FJ, et al. Comparison between conventional axillary block and a new approach at mid-humeral level. *Anesth Analg* 1997;84:1058–1061.
74. Tuohy SA, MacEvilly MA. Inadvertent injection of thiopentone to brachial plexus sheath. *Br J Anaesth* 1982;54:355–357.
75. Patterson KW, Scanlon P. An unusual complication of brachial plexus sheath cannulation. *Br J Anaesth* 1990;65:542–543.
76. Winnie AP. Interscalene brachial plexus block. Current researches. *Anesth Analg* 1970;49:455–466.
77. Brand L, Papper EM. A comparison of supraclavicular and axillary techniques or brachial plexus blocks. *Anesthesiology* 1961;22:226–229.
78. DeJong RH. Local anesthetics: adverse effects. Springfield, IL: Charles C. Thomas; 1977:254.
79. Ward ME. Interscalene approach to brachial plexus. *Anaesthesia* 1974;29:147–157.
80. Hickey R, Garland TA, Ramamurthy S. Subclavian perivascular block: influence of location of paresthesia. *Anesth Analg* 1989;68:767–771. *Reg Anesth* 1983.
81. Manara AR. Brachial plexus block, unilateral thoraco-abdominal blockade following the supraclavicular approach. *Anaesthesia* 1987;42:757–759.
82. Brown LD, Cahill DR, Bridenbaugh LD. Supraclavicular nerve block: anatomic analysis of a method to prevent pneumothorax. *Anesth Analg* 1993;76:530–534.
83. Knoblanche GE. Incidence and etiology of phrenic nerve block in association with supraclavicular brachial plexus block. *Anaesth Intensive Care* 1979;4:346–349.
84. Farrar MD, Scheybani M, Nolte H. Upper extremity block effectiveness and complications. *Reg Anesth* 1981;6:133–134.
85. Urmey WF, Talts KH, Sharrock ME. 100% incidence of hemidiaphragmatic paresis associated with interscalene brachial plexus anesthesia diagnosed by ultra sonography. *Anesth Analg* 1991;72:498–503.
86. Pere P, Pitkanen M, Rosenberg P. Continuous interscalene brachial plexus block decreases diaphragmatic motility and ventilatory function. *Acta Anaesthesiol Scand* 1992;36:53–57.
87. Urmey WF, McDonald M. Hemidiaphragmatic paresis during interscalene brachial plexus block: effect on pulmonary function and chest wall mechanics. *Anesth Analg* 1992;74:352–357.
88. Fujimura N, Anamba H, Tsunoda K, et al. Effect of hemi diaphragmatic paresis caused by interscalene brachial plexus block on breathing, patterns chest wall mechanics and arterial blood gases. *Anesthesiology* 1995;81:962–966.
89. Kayerker UN, Dick MD. Phrenic nerve paralysis following interscalene brachial plexus block. *Anesth Analg* 1983;62:536–537.
90. Hood J, Knoblanche G. Respiratory failure following brachial plexus block. *Anaesth Intensive Care* 1979;7:285–286.
91. Rau RH, Chan YL, Chuang HI. Dyspnea resulting from phrenic nerve paralysis after interscalene block in an obese male. *Acta Anaesthesiol Sin* 1997;35:113–118.
92. Neal JM, Moore JM, Kopacz DJ, et al. Quantitative assessment of respiratory and sensory function after supraclavicular block. *Anesth Analg* 1998;86:1239–1244.
93. Al-Kaisy AA, Chan VWS, Perlas A. Respiratory effects of low dose bupivacaine interscalene block. *Br J Anaesth* 1999;82:217–220.
94. Betts A, Eggan JR. Unilateral pulmonary edema with interscalene block. *Anesthesiology* 1998;88:1113–1114.
95. Candido KD, Sukhani R, Doty R, et al. Neurologic sequelae after interscalene brachial plexus block for shoulder/upper arm surgery: the association of patient, anesthetic, and surgical factors to the incidence and the clinical course. *Anesth Analg* 2005;100:1489–1495.
96. Barutell C, Videll F, Raich M, et al. Neurological complication following interscalene brachial plexus block. *Anaesthesia* 1980;35:365–367.
97. Lim EK, Pereira R. Brachial plexus injury following brachial plexus block. *Anaesthesia* 1984;39:691–695.
98. Bashein G, Thompson-Robertson H, Kennedy WF Jr. Persistent phrenic nerve paresis following interscalene brachial plexus block. *Anesthesiology* 1985;63:102–104.
99. Robaux S, Bouaziz H, Boisseau N, et al. Persistent phrenic nerve paralysis following interscalene brachial plexus block. *Anesthesiology* 2001;95:1519–1521.
100. Passannante PAN. Spinal anaesthesia and permanent neurologic deficit after interscalene block. *Anesth Analg* 1996;82:873–874.

101. Brockway MS, Winter AW, Wildsmith JA. Prolonged brachial plexus block with 0.42% bupivacaine. *Br J Anaesth* 1989;63:604–605.
102. Shantha TR, Evans JA. The relationship of epidural anesthesia to neural membranes and arachnoid villi. *Anesthesiology* 1972;37:543–557. Review. No abstract available.
103. Kumar A, Battit GE, Froese AB, et al. Bilateral cervical and thoracic epidural blockade complicating interscalene brachial plexus block – 2 cases. *Anesthesiology* 1971;35:650–652.
104. Ross S, Scarborough CD. Total spinal anesthesia following brachial plexus block. *Anesthesiology* 1974;39:458.
105. Edde S, Deutsch S. Cardiac arrest after interscalene brachial plexus block. *Anesth Analg* 1977;56:446–447.
106. McGlade DP. Extensive central neural blockade following interscalene brachial plexus block. *Anaesth Intensive Care* 1992;20:514–516.
107. Baraka A, Hanna M, Hammoud R. Unconsciousness and apnea complicating parascalene brachial plexus block, possible subarachnoid block. *Anesthesiology* 1992;77:1046–1047.
108. Dutton RP, Eckhardt WF III, Sunder N. Total spinal anesthesia after interscalene blockade of the brachial plexus. *Anesthesiology* 1994;80:939–941.
109. Norris D, Klahsen A, Milne B. Delayed bilateral spinal anesthesia, following interscalene block. *Can J Anaesth* 1996;43:303–305.
110. Majid A, van den Oever HL, Walstra GJ, Dzoljic M. Spinal anesthesia as a complication of brachial plexus block using the posterior approach. *Anesth Analg* 2002;94:1338–1339.
111. Al-Khafaji JM, Elias MA. Incidence of Horner's syndrome with interscalene brachial plexus block and its importance in the management of head injury. *Anesthesiology* 1986;64:127.
112. Sukhani CR, Barclay LJ, Aasen M. Prolonged Horner's syndrome after interscalene block: a management dilemma. *Anesth Analg* 1994;79:701–745.
113. Rollins M, McKay WR, Eshima RE. Airway difficulty after subclavian perivascular block. *Anesth Analg* 2003;96:1191–1192.
114. Plit ML, Chhajed PN, MacDonald P, et al. Bilateral vocal cord palsy following Interscalene brachial plexus block. *Anaesth Intensive Care* 2002;30:499–501.
115. Thiagarajah S, Moore E, Azar I, et al. Bronchospasm following interscalene brachial plexus block. *Anesthesiology* 1984;61:759–761.
116. Shah MB, Hirschman DA. Sympathetic blockade cannot explain bronchospasm following interscalene brachial plexus block. *Anesthesiology* 1985;62:847.
117. Durrani Z, Winnie AP. Brainstem toxicity with reversible “locked in syndrome” after interscalene brachial plexus block. *Anesth Analg* 1991;72:249–252.
118. Mani M, Ramamurthy N, Rao TLK, et al. An unusual complication of brachial plexus block and heparin therapy. *Anesthesiology* 1978;48:213–214.
119. Siler PL, Lief JS, Davis JS. A complication of interscalene brachial plexus block. *Anesthesiology* 1973;38:590–591.
120. Rosenberg PH, Lambert TS, Tarkkila T, et al. Auditory disturbance associated with interscalene brachial plexus block. *Br J Anaesth* 1995;74:89–91.
121. Schroeder LE, Horlocker TT, Schroeder DR. The efficacy of axillary block for surgical procedures about the elbow. *Anesth Analg* 1996;83:747–751.
122. Merrill DJ, Brodsky JB, Hentz RH. Vascular insufficiency following axillary block of the brachial plexus. *Anesth Analg* 1981;60:162–164.
123. Restelli L, Pingiroli D, Conoscente F, et al. Insufficient venous drainage following axillary approach to brachial plexus blockade. *Br J Anaesth* 1984;56:1051–1053.
124. Ott L, Neuberger L, Frey HP. Obliteration of the axillary artery after axillary block. *Anaesthesia* 1989;44:773–774.
125. Dudrick S, Masland W, Mishkin M. Brachial plexus injury following axillary artery puncture. *Radiology* 1967;88:271–273.