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SUPRACLAVICULAR REGIONAL ANAESTHESIA REVISITED

Philip Bruce Cornish

A thesis submitted in fulfillment of the requirements for the degree of Doctor of Medicine, The University of Auckland, 2015.
Supraclavicular block of the brachial plexus was long regarded as the quintessential skill of the regional anaesthetist: it was quick to perform, and effective at providing sensory and motor block of the arm, but significant skill was required to manage the risk of pneumothorax. Indeed, for this reason, it was often avoided by many practitioners for fear of both clinical and medicolegal consequences. More recently, there has been a resurgence of interest in supraclavicular block: the introduction of ultrasound, with its ability to visualize structures, in particular, improves the safety profile of the technique. This thesis undertakes a comprehensive reappraisal of the applied anatomy of the supraclavicular area, and evaluates how this knowledge might affect the complication/side effect profile of supraclavicular block. Initially, the aim was restricted to trying to lessen the risk of pneumothorax by using the mathematical principle of the tangent, with the anatomy of the area requiring a bend in the block needle, but the project evolved into the more comprehensive task of also trying to alter the risk of blocking the phrenic nerve, sympathetic chain, and recurrent laryngeal nerve. As secondary goals, the thesis aims to better place the technique in terms of its clinical utility, and examines how detailed knowledge of the anatomy can usefully be dovetailed with the emergent ultrasound technology. A number of anatomic and clinical studies were performed. These included examining the relationships between the clavicle, brachial plexus and chest wall, studying the block’s clinical profile, investigating the incidence of phrenic nerve block and studying the mechanism for its avoidance, and reevaluating the anatomic structures which surround the brachial plexus and influence flow and spread of injected solution. The results have added to the knowledge base of applied anatomy: in particular, they afford new insights into the role of the first rib, clavicle, and scapula. They have also challenged one of the traditional cornerstones of brachial plexus regional anaesthesia, the ‘sheath’. The study technique evolved to incorporate the modern technology, becoming ultrasound-guided axillary tunnel block. The clinical versatility of this technique and its ability to avoid the phrenic nerve are clear advantages. Together, these observations enhance our
understanding of the anatomic dynamics involved in brachial plexus blockade, and the thesis presents a new model based on the rigid anatomy surrounding the plexus.
DEDICATION

I wish to dedicate this thesis to my father, Charles Bruce Cornish, MBChB, FRACS (Edin.), FFARACS, 1921-2004, Otolaryngologist and Head & Neck Surgeon, for encouraging my enquiring mind.
This thesis is a synthesis of the following publications:


I wish to acknowledge all my collaborating colleagues, who have listened with patience and interest as I developed the concepts in this thesis. I wish to thank my supervisor Associate Professor Jenny Weller for her support and advice. I also wish to acknowledge the skilled assistance of my copy editor, Dr Sally Bolitho.
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SUMMARY OF CHAPTERS

In Chapter 1, I review the anatomy of the sensory supply of the upper extremity, and the historical development of supraclavicular block, with particular reference to some key issues and concepts. This review provides the anatomic framework and clinical rationale for the development of this project.

In Chapter 2, the anatomy is reevaluated to more precisely define the target zone. Geometric modelling is utilized to lessen the risk of pneumothorax, and the theoretical basis and potential advantages of the bent needle are described. This chapter incorporates work from the following publications:


In Chapter 3, I present data from the initial experience with the bent needle technique, confirming potential advantages of the technique. This chapter incorporates work from the following publication:


In Chapter 4, I present our work on the incidence of phrenic nerve block related to the bent needle technique. This specifically examined my belief that one advantage of the technique might be a very
low incidence of phrenic nerve block. This chapter incorporates work from the following publication:


In Chapter 5, I present our work on the mechanisms we believed responsible for the very low incidence of phrenic nerve block, and introduce a new anatomic paradigm - the ‘axillary tunnel’. This chapter incorporates work from the following publication:


In Chapter 6, I present our work challenging the concept of the brachial plexus sheath, which evolved from our finding of the axillary tunnel. This chapter incorporates work from the following publications:


In Chapter 7, I integrate the anatomic findings of my research work with the use of ultrasound for regional anaesthesia, and I convert the bent needle technique to an ultrasound-based technique, using the knowledge and insights from this body of research. This chapter incorporates work from the following publications:


In Chapter 8, I summarise the key findings of my research, comment on deficiencies, and point to future directions for research.
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**CHAPTER 2, SECTION 2.3, PAGE 22.**
Cornish Pb, Greenfield LJ, O'Reilly M, Allan L. Indirect vs direct measurement of brachial plexus depth. Anesth analg 1999;88:1113-6

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**CHAPTER 2, Section 2.3, page 22**
Cornish PB, Nowitz M. A magnetic resonance imaging analysis of the infraclavicular region: can brachial plexus depth be estimated before needle insertion? Anesth Analg 2005; 100:1184-8

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**CHAPTER 6, page 63**


| Nature of contribution by PhD candidate | Study design, placed nerve catheters, image analysis, manuscript preparation |
| Extent of contribution by PhD candidate (%) | 85% |

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CHAPTER 4, page 49

Nature of contribution by PhD candidate: Study design, study coordination, placed nerve blocks and catheters, principal author
Extent of contribution by PhD candidate (%): 75%

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**CHAPTER 4, page 49**

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CHAPTER 5, page 56:
Cornish PV, Leaper CJ, Hahn J. The 'auxiliary tunnel': an anatomic reappraisal of spread during brachial plexus blockade. Anesthesiology 2007;104:1288-91

Nature of contribution by PhD candidate: Study design, placed nerve catheters, image analysis, wrote manuscript

Extent of contribution by PhD candidate (%): 85%

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Supraclavicular block of the brachial plexus was long regarded as the quintessential skill of the regional anaesthetist: it was quick to perform, and effective at providing sensory and motor block of the arm, but significant skill was required to manage the risk of pneumothorax. Indeed, for this reason it was often avoided by many practitioners for fear of both clinical and medicolegal consequences. More recently, there has been a resurgence of interest in supraclavicular block: the introduction of ultrasound, with its ability to visualize structures, in particular, improves the safety profile of the technique.

When embarking upon this project, the intended task of altering the risk of pneumothorax associated with supraclavicular block seemed relatively straightforward. Following the principle that if one is not aiming at a target, then the target will be missed, a needle tip not directed at the lung ought not to cause a pneumothorax. This could be achieved using a tangent to the chest wall. It became then simply a matter of adapting regional anaesthetic technique to anatomic demands, since the ability to manipulate anatomy was limited. The anatomy of the supraclavicular area required a bend in the needle to reach the tangent.

This thesis undertakes a comprehensive reappraisal of the applied anatomy of the supraclavicular area, and evaluates how this knowledge might affect the complication/side effect profile of supraclavicular block. As a secondary goal, the thesis aims to better place the technique in terms of its clinical utility. Supraclavicular block is recognized as an effective technique for shoulder surgery, and might be a suitable alternative to the use of interscalene block, which is restricted by side effects such as phrenic nerve block. Finally, the work presented here examines how this knowledge could usefully be dovetailed with the emergent ultrasound technology.

As the project developed, it became quickly apparent that some of the fundamentals of our understanding of regional anaesthesia of the upper extremity were open to question: e.g. terminology,
neural structures, and the brachial plexus sheath. For this reason, there was a need to return to basics, and reconstruct our understanding and application of brachial plexus regional anaesthesia from the very beginning.

1.1 An introduction to the anatomy of the sensory innervation of the upper extremity (1,2)

The upper extremity derives its sensory supply from three sources; the supraclavicular nerves, the intercostobrachial nerve, and the brachial plexus. The supraclavicular branches of the superficial cervical plexus innervate the skin over the shoulder. The intercostobrachial nerve, which is the lateral cutaneous branch of the second thoracic intercostal nerve, innervates the skin of the upper inner arm. The brachial plexus innervates all other structures in the upper extremity.

The brachial plexus is derived from the ventral rami of the fifth to eighth cervical nerves and the greater part of the ramus of the first thoracic nerve. Small contributions may be made by the fourth cervical and the second thoracic nerves. The ventral rami emerge from their respective foraminae and pass between the anterior and middle scalene muscles, where they are joined by sympathetic fibres.

The order of the rami has significance for their distribution to the upper extremity, and this is incorporated within The American Spinal Injury Association’s (ASIA) template of ‘key sensory points,’ which provides a simple template for rapid neurological assessment based on the dermatomes: C5 is a point in the lateral aspect of the arm just proximal to the elbow; C6 is a point in the dorsum of the thumb; C7 is a point in the distal part of the middle finger; C8 is a point in the dorsum of the little finger; and T1 is a point in the medial aspect of the forearm just distal to the elbow. The ASIA also provides a template for assessment by myotomal pattern: C5 is represented by shoulder abduction; C6 is represented by wrist extension; C7 is represented by elbow extension; C8 is represented by finger flexion; and T1 is represented by abduction of the fingers. The rami are also the basis of classification of the deep tendon reflexes: C5 is represented principally by the biceps reflex; C6 is represented principally by the brachioradialis reflex; and C7 is represented principally by the triceps reflex.
After passing the margins of the scalene muscles, the fifth and sixth ventral rami unite to form the superior trunk; the seventh ventral ramus continues alone as the middle trunk; and the first thoracic ventral ramus unites with the eighth cervical ramus to form the inferior trunk. The trunks have a cranial to caudad distribution in the upper extremity: the superior trunk supplies the shoulder, the inferior trunk supplies the hand, and the middle trunk supplies the structures in between.

Lateral to the first rib, the separation of each trunk into an anterior and a posterior part signifies a fundamental reorganization of the nerve bundles that originally supplied the ventral parts of the limb from the nerve bundles that supplied the dorsal parts of the limb. In this respect, the lateral and medial intermuscular septae (extending outward from the periosteum of the humerus) and the investing brachial fascia surrounding the muscle masses produce a clear separation of the arm into anterior and posterior compartments. In the forearm, the radius and ulna are similarly interconnected to the investing antebrachial fascia by an intermuscular septum. The compartment and structures anterior to the bone and fascial plane, or axis, of the limb are designated preaxial, and the structures behind the bony and fascial axis are designated postaxial.

The anterior and posterior divisions of the fifth, sixth, and seventh nerves are of approximately equal size, while the posterior division of the eighth nerve is smaller and that of the first thoracic nerve is very small (or may be entirely lacking).

All of the posterior divisions unite to form the posterior cord; hence they can be thought of as one in functional terms, and are responsible for innervating all postaxial structures in the upper extremity. They include contributions from all of the contributing nerve roots C5-T1. The anterior divisions of the superior and middle trunk, containing fibres from C5-7, unite to form the lateral cord. The anterior division of the inferior trunk, containing fibres from C8-T1, continues as the medial cord. Both the lateral and the medial cords are destined for the anterior portion of the limb.

The cords are named not by reference to the destination of their distribution, but rather by the relations they exhibit to the axillary artery – lateral, medial, and posterior – at the point where that
artery is crossed by the pectoralis minor muscle.

The lateral and medial cords give rise to three major terminal branches beyond the coracoid process in the distal axilla: the median, ulnar, and musculocutaneous nerves. In this regrouping, a large segment of each of these two cords separates and joins the other on the anterior surface of the axillary artery to form the median nerve. The remainder of the lateral cord constitutes the musculocutaneous nerve, and, likewise, the remainder of the medial cord becomes the ulnar nerve. The posterior cord gives off the axillary nerve at the lower border of the subscapularis muscle, and the remainder of the posterior cord becomes the large radial nerve.

There are a number of nerves which arise from the rami, trunks, and cords at levels above the formation of the terminal branches:

1. From the rami: nerves to the anterior, middle, and posterior scalene muscles, and longus cervicis muscles arise from the lower four cervical ventral rami as they emerge from their intervertebral foraminae. A contribution from the fifth cervical ventral ramus is made to the phrenic nerve at the lateral border of the anterior scalene muscle. The dorsal scapular nerve arises from the ventral ramus of C5, and the long thoracic nerve arises from the ventral rami of C5-7.
2. From the trunks: the nerve to subclavius originates from the anterior aspect of the superior trunk, and the suprascapular nerve arises from the posterior aspect of the superior trunk.
3. From the cords: the lateral pectoral nerve arises from the lateral cord, the medial pectoral nerve arises from the medial cord, the medial brachial cutaneous nerve arises from the medial cord, the medial antebrachial cutaneous nerve arises from the medial cord near the origin of the ulnar nerve, and the subscapular nerves arise from the posterior cord.

There are seven major terminal nerves of the brachial plexus:

1. The axillary nerve: motor to the deltoid and teres minor muscles; sensory to the shoulder joint and skin of the upper lateral arm.
2. The radial nerve: motor to all postaxial musculature (triceps, brachioradialis, extensor carpi...
radialis longus, extensor carpi radialis brevis, extensor digitorum, extensor digiti minimi, extensor carpi ulnaris, supinator, extensor pollicis brevis, extensor pollicis longus, and extensor indicis muscles); sensory to the elbow and wrist joints and skin of the posterior aspect of the arm, forearm, and hand.

3. The musculocutaneous nerve: motor to biceps and coracobrachialis; sensory to the skin of the anterolateral forearm.

4. The medial brachial cutaneous nerve: sensory to the skin of the medial arm.

5. The medial antebrachial cutaneous nerve: sensory to the skin of the medial forearm.

6. The ulnar nerve: motor to the flexor carpi ulnaris, the ulnar portion of flexor digitorum, and all intrinsic muscles of the hand other than the abductor pollicis brevis, opponens pollicis, flexor pollicis brevis, and the two most radial lumbricals of the hand; sensory to the elbow and wrist joints and the skin of the ulnar aspect of the palm.

7. The median nerve: motor to the pronator teres, flexor carpi radialis, palmaris longus, flexor digitorum superficialis, abductor pollicis brevis, opponens pollicis, and flexor pollicis brevis muscles, and the two most radial lumbricals of the hand; sensory to the wrist joint and skin of the lateral aspect of the palm.

1.2 Why has supraclavicular block been so favoured, and yet so feared?

The first recorded descriptions of supraclavicular block were by surgeons who blocked the brachial plexus under direct vision (4, 5). In 1911, Hirschel (6) and Kulenkampff (7) independently described the first percutaneous blocks, beginning a long tradition of regional anaesthesia in this area.

In 1949, Bonica and Moore (8) published the first of two major series of supraclavicular blocks, keen to promote the technique. Their caseload included procedures on all territories innervated by the brachial plexus. However, in the same year, Accardo and Adriani (9) advocated for axillary block because of the risk of pneumothorax with supraclavicular block, and this stance was received favorably.
The more distal axillary technique, by virtue of its simplicity, safety and consistency of results, became popular. In the early 1960s, comparative studies of axillary versus supraclavicular block reinforced this position (10, 11). Subsequently, two publications renewed interest in supraclavicular block.

In 1964, Winnie and Collins published their technique of supraclavicular block based on the concept of the subclavian perivascular space (12). In 1983, Lanz et al. documented the reliability and versatility of the supraclavicular block (13) using techniques described by both Kulenkampff and Winnie, and showed that brachial plexus block at this level was more likely to block all the elements of the brachial plexus than either the axillary or interscalene blocks. These publications paved the way for the surge in popularity of supraclavicular block which occurred with the introduction of ultrasound in the late 1980s, and the ability to visualize the anatomy revolutionised practice.

There are a number of published series of supraclavicular block that detail complications, of which pneumothorax has been the most common. Bonica and Moore quoted an incidence of pneumothorax of 0.82% from their series of 1048 blocks, although none of these patients required specific therapy (8). Their review of the literature suggested, however, that the incidence of pneumothorax could be as high as 2%. A larger cohort of 1500 blocks reported by the same authors had a similar incidence of pneumothorax of 0.66%, again requiring no specific therapy (14). Bridenbaugh cites an incidence of 0.5% (15).

The extant literature also details a number of technical variations that can reduce the risk of pneumothorax including modifications of the direction of needle insertion (8, 16, 19-21), alterations of the point of needle insertion (20,21), palpation of the first rib (18), needle design modification (17), and even avoidance of supraclavicular block (9).

As noted above, Accardo and Adriani (9) advocated avoidance of the supraclavicular area, placing their needle in the axilla instead, and using a multiple injection technique to block median, radial, ulnar, and musculocutaneous nerves for surgical anaesthesia from the elbow to the hand. Their specific concern with supraclavicular block related to the risk of pneumothorax, suggesting that it was a
Bonica and Moore (8) strongly advocated for supraclavicular block. They were using the technique for surgeries from the shoulder to the hand in a military environment. Interestingly, they commented that their principal competitor was not another block technique, but rather the newly introduced ‘pentothal sodium’ (p.65) which was considered by some as ‘the simplest and fastest agent to use in all cases’ (p.65). Their needle was aimed ‘caudad, mesiad and dorsad toward the spinous process of the third thoracic vertebra’ (p.69) from a midclavicular position, which they described as a modification of supraclavicular block. They confidently predicted contact with the first rib should the needle fail to first contact the plexus. Nonetheless, amongst their series of 1,048 blocks they reported nine cases of pneumothorax.

Di Florio (16) placed the needle two centimetres posterior to the midpoint of the clavicle, and inserted it directly caudally for blocks in ten patients who were undergoing surgery of the forearm and hand. The author commented that this kept the needle lateral to the first rib and pleura. He reported no cases of pneumothorax.

Alternatively, Fortin and Tremblay (17) used a short needle to try to avoid over-insertion, based on the observation that paraesthesias were frequently elicited during preliminary subcutaneous infiltration of local anaesthetic with a half-inch needle prior to block needle insertion. The midpoint of the clavicle was the reference point for initial needle insertion, which occurred ‘downward, backward and inward’ (p.34). The first rib was not regarded as a potential point of contact as it indicated over-insertion of the needle; however, this contact still occurred 39 times in their series of 82 patients. The authors also used ultrasound waves in a few cases to attempt to enhance diffusion of the injected solution after block placement, but without success.

Korbon et al. (18) attempted to palpate the first rib behind the midpoint of the clavicle in the supraclavicular fossa, and guided the needle perpendicular to the skin in all planes between the index and middle fingers, which were positioned on either side of the first rib. The average weight of the 28
patients was 76 kg, and the first rib was contacted on three occasions. The authors claimed ease of rib palpation in all but the most obese patients.

Moorthy et al. (19) suggested an injection point in the supraclavicular fossa behind the subclavian artery. A Doppler flow probe was used to mark the axillary artery position below the clavicle and a line was drawn between this and the subclavian artery in the supraclavicular fossa. The direction of needle insertion was parallel to the line marking the course of the artery (i.e. caudally, posteriorly, and laterally toward the axilla). A failure rate of 12% was recorded.

Pham-Dang et al. (20) advocated approaching the brachial plexus from between the two heads of the sternocleidomastoid muscle, across the floor of the posterior triangle of the neck. Their goals were to design a technique that minimized the risk of pneumothorax, to provide a safer alternative to interscalene block for shoulder surgery, to facilitate catheter insertion, and to simplify landmarks. They dismissed ultrasound as too expensive. Their anatomic analysis did not mention that their initial needle insertion must pass directly across the anterior aspect of the cupola of the lung.

Winnie et al. (12) based their technique on their concepts of the subclavian perivascular space and the brachial plexus sheath. Their needle approach was based on their analysis of the anatomic dimensions of the brachial plexus sheath: this suggested greater safety in a directly caudad direction at the base of the groove between the anterior and middle scalene muscles, from the point at which the subclavian artery becomes palpable. Since these muscles insert into the first rib, the needle running parallel to them would automatically find the first rib if the plexus was missed. This approach corrected what these authors regarded as illogical features of other techniques, such as ‘needle insertion is about one centimeter above the midpoint of the clavicle … direction of injection is mesiad, caudad and dorsad’ (p.357). They did, however, advocate for the use of a short needle, although this was not attributed to Fortin and Tremblay.

Brown et al. (21) applied the physical principle of the plum-bob to place the needle behind the clavicle, with the patient in the supine position. The point of insertion was immediately adjacent to the
lateral head of the sternocleidomastoid muscle. Although the authors claimed the ability to minimise the risk of pneumothorax using their technique, their data show that the lung was in the line of needle insertion in 25% of their analysed subjects.

All of these variations on the earlier practice of supraclavicular block had the same disadvantage. The actual position of the critical structures – the lung, the plexus, and the first rib – had to be assumed. Inevitably, this led to uncertainty and an increase in the degree of perceived risk.

This situation changed with the introduction of ultrasound to regional anaesthesia in the late 1980s, as structures were now able to be clearly visualised (See Chapter 2.6 below).

1.3 Other matters to consider

1.3.1 The phrenic nerve.

Phrenic nerve block is a common complication of supraclavicular block, and, for this reason, the technique is not recommended for those with diminished respiratory reserve.

The phrenic nerve is the sole motor nerve to the diaphragm, and also provides sensation to its central part. It is a monofascicular nerve which arises by a large root from the fourth cervical ventral ramus, and is reinforced by smaller contributions from the third and fifth cervical ventral rami. It makes its appearance at the lateral border of the anterior scalene muscle, descends vertically over the ventral surface of this diverging muscle, and enters the chest along its medial border. The nerve lies behind the prevertebral layer of cervical fascia, and is crossed by the transverse cervical and suprascapular vessels. Accessory phrenic nerves are common as aberrant contributions to the phrenic nerves. They frequently arise as branches of other cervical or brachial plexus nerves. The most frequent accessory phrenic nerve is a branch of the nerve to the subclavius muscle (22).

In a paper describing anatomical variations of the phrenic nerve (23), Bigeleisen commented that the accessory phrenic branch of the phrenic nerve is often in close proximity to where a supraclavicular block is placed.
Kessler et al. measured the distance between the phrenic nerve and the brachial plexus at different levels in the neck (24). They found a mean distance of 0.18cm at the C5-6 level, and 1.08cm at a point three centimetres more caudal. They commented that the results of other investigators, which showed volume and other manipulations to have little effect in avoiding the phrenic nerve at C5-6 level, were not surprising given the proximity of the structures (25). They suggested that injecting at a level three centimetres caudal to C5-6 might be a safer option to avoid the phrenic nerve, perhaps also using lower volumes of injectate.

While phrenic nerve block is more commonly associated with interscalene block (with a published incidence of 100% (26) for single shot block and 50% (27) for continuous block), it has a documented incidence of 20-80% with supraclavicular block (18, 28-32), depending on the particular technique and volume injected.

The explanation for the lower incidence of phrenic nerve block with supraclavicular block is a matter of some debate: it may reflect a greater distance to the phrenic nerve on the anterior aspect of the anterior scalene muscle; it may be further to spread between the anterior and middle scalene muscles to the originating ventral rami C3-5; or another mechanism may be responsible.

There is evidence in the literature that phrenic nerve block may cause significant respiratory distress. In one study of healthy volunteers, 10% of those with a hemidiaphragmatic paresis were symptomatic (i.e. developed dyspnoea) (33), while in another study 38% experienced dyspnoea (28). Phrenic nerve block is associated with a 25% reduction in forced vital capacity after single-shot interscalene block (33), and up to 50% with continuous interscalene block (27). However, Neal et al. (31) were unable to demonstrate an alteration in respiratory function when phrenic nerve block occurred in association with supraclavicular block in four fit volunteers. They did, however, demonstrate a significant increase in thoracic excursion in these patients, which likely counteracted other negative effects from the hemidiaphragmatic paresis. The authors concluded that supraclavicular block was not suitable in those with preexisting significant respiratory compromise.
There have also been reports of lobar collapse associated with phrenic paresis (34) and persistent symptomatic phrenic nerve paresis (35-37).

This compromise of pulmonary function has long been considered too great to risk this complication in those with a preexisting decrease in respiratory reserve (38).

There have been attempts to minimize the risk of this complication (39-44), almost exclusively related to interscalene block, including: alterations in volume and dose, changing the precise point of injection in the interscalene space, applying digital pressure to try and influence the pattern of spread of injected solution, and, more recently, the use of ultrasound guidance (45-50). These attempts have, however, been largely unsuccessful in adequately altering the risk, perhaps because the delivery point has remained largely unchanged.

Recently, it has been suggested that low volume injections under ultrasound guidance can avoid phrenic nerve block during interscalene block (51, 52). This does not, however, appear to be an entirely consistent phenomenon (53).

Renes et al. (46) did achieve an incidence of 0% phrenic block with supraclavicular block using ultrasound. This has significance for this project, as the authors were injecting in the same tissue plane – posterior to the artery – as the project technique. (For further discussion, see Chapter 5 below.)

1.3.2 Nerve injury.

Neurological sequelae of brachial plexus block have been identified as a problem for many years. In their 1958 report (54) of several cases of nerve injury from brachial plexus block and a review of the literature, Wooley et al. identified a series of publications reporting nerve injury associated with brachial plexus block (8, 55-63). They noted though that it was more usual to find no reference to neurological damage in publications about brachial plexus block, which infers underreporting. The most important feature of the presentation of each of their cases was the persistence of neurological symptomatology long after the immediate postoperative period. Suggested potential mechanisms for
nerve injury included mechanical trauma and local anaesthetic toxicity.

A series of publications by Selander et al. (1977-1993) explored the issue of neurological injury associated with peripheral nerve block in much greater detail (64-68).

Selander et al.’s seminal paper on needle point trauma (64) examined the incidence and severity of fascicular injury when a nerve was penetrated by a needle. Bevel length (long versus short) and bevel orientation to the fascicle (transverse versus parallel) were tested. Their results showed that when a nerve was penetrated by a needle with its bevel parallel to the nerve fibres, a long bevel caused less fascicular injury than a short bevel did. They also found that a long bevel in parallel orientation to the fascicle caused less injury than in transverse orientation. There was, however, a lower frequency of nerve penetration with the short-bevelled needles. This paper had immense influence on subsequent regional anaesthesia needle design (69) which has subsequently favoured short bevels. It is, however, difficult to interpret from Selander et al.’s results whether the decreased frequency of injury with the short-bevelled needle related to the difficulties they had impaling the nerve with this particular needle.

In 1992, Rice and McMahon produced an important update to Selander et al.’s work on needle tip trauma (70). They examined both short-term and long-term sequelae of nerve impalement by needles in an animal model. While the short term results were the same as those of Selander et al., the results at 28 days suggested recovery of lesions from long-bevelled needles, but ongoing processes in nerves damaged by short-bevelled needles. Distal axonal degeneration was only observed in specimens examined after seven and 28 days, and only in nerves impaled by either short-bevelled needles in both bevel orientations or long-bevelled needles with transversely-oriented bevels. Behavioural changes were only evident in those animals exposed to short-bevelled needles in either bevel orientation. Sensory changes occurred in those animals exposed to short-bevelled needles in either bevel orientation and those exposed to long-bevelled needles in transverse orientation, but all resolved by 28 days. Rice and McMahon concluded that should accidental nerve fascicle penetration occur, then the ‘frequency, severity and time course of intrafascicular injury would be greater when short-bevelled, as opposed to
long-bevelled, needles were used’ (p.438). It is not clear why this paper did not result in a change in needle bevel configuration.

More recently, Sala-Blanch et al. repeated this type of experimental study (71) in a cadaveric model using the multifascicular sciatic nerve for needle puncture. The investigators noted a low incidence of fascicular injury which they attributed to a high amount of connective tissue surrounding the fascicles. The needle bevel was oriented transverse to the line of the fascicles, and standard regional block needles were used. The study did, however, confirm Rice’s and McMahon’s findings that a transversely oriented blunt needle causes damage when it penetrates a fascicle.

Selander’s work (cited above) also examined other potential factors involved in the production of neurological deficits, including the elicitation of paraesthesiae, the presence of adrenaline in the injected solution, and the neurotoxicity of local anesthetic drugs. The results of these publications pointed to the importance of mechanical trauma, ischaemia, and drug toxicity in the production of neurological deficits related to peripheral nerve blocks.

Incidence of nerve injury was not systematically examined until the work by Watts and Sharma (72) and Barrington et al. (73), which established it at 0.22–0.4%. It was hoped that the introduction of ultrasound would lessen the incidence of nerve injury, but the work by Barrington et al. has failed to demonstrate this (73).

In 2006, Bigeleisen took a different approach to the issue of neural injury, first by suggesting in a paper published in the journal Anesthesiology that intraneural injection did not necessarily cause injury and was, therefore, not the problem it had previously been considered to be (74). The difficulty posed by his findings was that after he advanced the needle to the desired endpoint, he injected a few millilitres and if the injectate appeared to be intraneural he withdrew the needle. This is not what most practitioners would regard as a significant intraneural injection, where the entire volume of 10-20ml would be injected. Additionally, since it is possible to achieve a successful block without injecting inside a nerve, why would there be interest in doing the opposite, given the known danger? Bigeleisen then
demonstrated that a nerve stimulator was able to accurately demonstrate intraneural placement of a needle with a stimulating current set at 0.2mA (75), thereby providing a quantitative monitor of needle position.

More recently, the use of pressure manometry has been proposed as a way of avoiding intraneural injection (76-79). Questions remain over the sensitivity and specificity of this technique.

Perhaps, however, a combination of the different techniques – nerve stimulation, ultrasound-guidance, needle configuration, or pressure manometry – may lessen the chances of nerve injury. The difficulty of proving any strategy remains with the low incidence of injury, and the large numbers which would, therefore, be required in a randomized controlled trial.

1.3.3 Interscalene or supraclavicular block for shoulder surgery?

Interscalene block has been considered the technique of choice for shoulder surgery for many years. This can be attributed to its ability to reliably block the nerve roots C5 and C6 (the source of sensory supply to the shoulder joint) in the interscalene space.

There has, however, been concern over the side effects and safety profile of this technique. In 1991, Tuominen et al. published a case report of unintentional vertebral arterial cannulation associated with a loss of consciousness and cardiovascular collapse while attempting to site an interscalene catheter (80). In 2000, Benumof described four cases of spinal cord injury following interscalene block performed under general anaesthesia (81). The focus of responses to this publication centred on placement of the block in anaesthetized or heavily sedated patients (82-85), and an American Society of Regional Anesthesia expert panel subsequently advised against block placement under these conditions (86). In 2012, Yanovski et al. published the case report of a death that appeared to follow the postoperative top-up of an interscalene catheter (87). In 2013, Kaufman et al. published a series of 14 patients with persistent phrenic nerve paresis post-interscalene block, who subsequently underwent exploration, neurolysis, and nerve grafting for injuries to the phrenic nerve (88). The authors felt that
either mechanical trauma or pharmacological toxicity was the underlying cause for the complication, and noted that the phrenic nerve was small and, therefore, susceptible to damage. The accompanying editorial questioned the wisdom of continuing with a regional technique which, over time, had been associated with this and other serious potential side effects (89). Other commentators counselled against attributing blame too hastily (90, 91).

Supraclavicular block, in the meantime, has been steadily gaining favour as an effective alternative to interscalene block (92, 93).

1.3.4 The sheath of the brachial plexus.

The story of the brachial plexus sheath started with Reding (94), who, in 1921, described the connective tissue as enveloping the nerves in the axilla, and noted that he was able to block the median, radial, and ulnar nerves with a single injection. In 1958, Burnham (95) and Eather (96) again described connective tissues surrounding the nerves and vessels in the axilla, although Eather pointed out that blocks were most consistent if a large volume of solution was injected. This notion was reiterated by de Jong in 1961 (97), whose intention was to also block the axillary and musculocutaneous nerves. De Jong also calculated, using the formula for the volume of a cylinder, that a minimum of 42ml would be necessary to reach the cords of the plexus from the axilla. Winnie was later able to demonstrate in a dye study in a patient that an injection of 50ml could indeed reach the level of the first rib from the axilla (12).

In his 1964 paper, Winnie extended the concept of the axillary sheath, suggesting that it was merely the final part of a tubular prolongation of the prevertebral fascia. The nerve roots emerged ‘between the two walls of fascia covering the anterior and middle scalenes’ (i.e. they entered the interscalene or subclavian perivascular space). As the roots passed down through this space, they converged to form the trunks of the brachial plexus, and together with the subclavian artery invaginated the scalene fascia which became the axillary sheath as it passed under the clavicle. The important
concept for the anaesthetist was that of a continuous fascia-enclosed space extending from the cervical transverse processes to several centimeters beyond the axilla, or from the roots of the brachial plexus to the great nerves of the upper arm. Winnie likened brachial plexus anaesthesia to epidural anaesthesia, where, once the space had been entered, only a single injection was needed, and the extent of effect would depend upon the volume injected and the level of injection.

In 1979, Winnie published further work detailing factors that influenced distribution of injected solution within the brachial plexus sheath (98): these included the head of the humerus and site of needle placement for axillary block, and digital pressure for interscalene block. This information modified Winnie’s concept of the sheath (as described in the previous paragraph).

Thompson and Rorie then published a cadaveric anatomic study in which the sheath appeared to be a multi-compartmented structure with septae extending inwards from the outer margins, creating a compartment for each nerve (99). This was followed by another cadaveric study which demonstrated that the septae identified by Thompson and Rorie were incomplete (i.e. that the compartments were interconnected) (100).

More recently, Klaastad et al. examined local anaesthetic distribution in a clinical model of axillary block using magnetic resonance imaging to demonstrate uneven distribution of local anaesthetic which corresponded to incomplete block (101).

Moayeri et al. quantified the amounts of connective tissue around the neurovascular bundle from proximal to distal points. There was more connective tissue distally, and the monofascicular nerve roots in particular were the least protected (102).

The concept of a simple tubular prolongation of the prevertebral fascia, as described by Winnie in his original publication, was therefore modified substantially by these later studies.
2.1  Anatomy revisited: an alternative anatomic explanation for the clinical reputation of the supraclavicular block

Incorporating the following publications, with reference numbers:


This chapter revisits the standard definitions and terminologies used in regional anaesthesia of the brachial plexus, and suggests an alternative approach as an anatomic template for planning the revised technique.

The most widely accepted explanation for the effectiveness of supraclavicular block is that it targets the anatomic location where the components of the brachial plexus are most compactly arranged (20). Indeed, this is the point at which the originating nerve roots join together to form the three trunks – superior, middle, and inferior – of the plexus.

An alternative explanation could be that supraclavicular block occurs at plexus level (as opposed to nerve root or terminal nerve level), and one would, therefore, expect to block all elements of the plexus (13). Let us further explore this idea.

It has been generally accepted that the nerves of the brachial plexus can be accessed at several levels: interscalene, supraclavicular, infraclavicular, and axillary. The interscalene block occurs at an axial level of approximately C6, between the anterior and middle scalene muscles which arise from the transverse processes of the cervical vertebrae (C3-6 for anterior scalene, C2-7 for middle scalene) and insert into the first rib. The supraclavicular block occurs at the base of the neck posterior to the clavicle, with the first rib forming its inferior boundary. The infraclavicular block occurs inferior to the middle
third of the clavicle, just medial to the coracoid process of the scapula. And the axillary block occurs in the armpit.

While it is true that the nerves accessed at these various points all have a relationship to those at the other points, it is not true that the neural components at each level are the same: at interscalene level, there are nerve roots; at supraclavicular level, the trunks form; at infraclavicular, level there are the cords; and, at axillary level, the terminal nerves are present.

In clinical terms, the various levels give rise to different block profiles which reflect these anatomic differences. The interscalene most reliably blocks C5 and C6 nerve roots for shoulder surgery. The supraclavicular (by blocking trunks) and the infraclavicular (by blocking cords) affect a wider territory: both have traditionally been recommended for the arm, but not the shoulder. And the axillary most reliably blocks the nerves supplying the hand, and, for this reason, is widely used for surgery of the hand. With these differences in mind, let us revisit some definitions:

a. ‘Plexus’ - an interlacing network, as of nerves. Hence ‘brachial plexus’: formed by the joining of the ventral primary divisions of the 5th to the 8th cervical and the 1st thoracic nerves, and giving origin to the nerves of the upper extremity (103). The network begins with the formation of the three trunks, and ends with the formation of the seven terminal nerves. Between these points of origin and termination, the nerves interconnect by way of the divisions and then the cords. According to this definition, the brachial plexus is located posterior and inferior to the middle third of the clavicle, and constitutes the trunks, divisions, and cords (104).

b. ‘Axilla’ – a pyramidal-shaped area at the junction of the upper limb and the chest, which has four sides, an apex, and a base (See Figure 1). The base is the concave armpit, the anterior wall is the pectoral fascia and muscles, the posterior wall is the scapula and subscapularis muscle, the lateral wall is the humerus, the medial wall is the chest wall and serratus anterior muscle, and the apex is formed by the
convergence of bones of the three major walls (the clavicle, scapula, and first rib) (105). The apex of the axilla also represents the lateral aspect of the supraclavicular fossa (106).

![Image of the axilla](image)

**FIGURE 1: The Axilla.**

Following the definitions of plexus and axilla given above, the axillary block is located in the base of the axilla and anaesthetizes peripheral nerves, particularly those supplying the hand (106). The interscalene block is located between the anterior and middle scalene muscles, and anaesthetizes the nerve roots, particularly those supplying the shoulder, C5, and C6. The supraclavicular block, at the level of the first rib, blocks the trunks and, with distribution of local anaesthetic up the neck between the scalene muscles, also blocks the nerve roots (107). The infraclavicular block, medial to the coracoid process, anaesthetizes the cords. The administration of large volumes of local anaesthetic can, to some extent, overcome these patterns of spread (12), but they remain the fundamental patterns, particularly
with the use of lower volumes under ultrasound guidance.

2.2 Where is the lung, and can a needle reach the brachial plexus without threatening the lung?

I believe that this question is most readily answered by studying images such as the one shown in Figure 2. This is a coronal magnetic resonance image of the left upper chest wall and neck, with specific structures (including the brachial plexus, chest wall, and lung) labeled for ease of interpretation. The danger areas in the supraclavicular fossa lie either deep or medial to the fossa. The challenge is to reach the brachial plexus without threatening the lung.

**Figure 2: Supraclavicular Block.**
The undesirable structures lie either medial or deep.
In geometry, a tangent is a straight line which touches a curved line at only one point. Figure 3 applies this geometric principle to the chest wall. In this figure, the straight line runs tangentially to the curved chest wall. A needle tip inserted along this line will not penetrate the chest wall to cause a pneumothorax.

However, there were two anatomical obstacles to achieving this needle position: the clavicle (laterally), and the neck (medially). My solution to this dilemma was to place a small bend in the shaft of the needle (Figure 3) so that initial insertion of the needle was not crowded by the neck, and the needle could then be guided under the clavicle without being further restricted by the neck.

**Figure 3: A Tangent to the Chest Wall.**
There were other potential benefits to the proposed strategy. The bend would potentially permit the needle tip to be better aligned with the plexus, and might thereby facilitate catheter insertion. The needle tip would also be located further away from structures which one did not wish to block: e.g. the recurrent laryngeal nerve, the phrenic nerve, and sympathetic chain. The alignment of the needle tip with the long axis of the plexus might lessen the chances of nerve injury.

While the clavicle was regarded as an obstruction at a conceptual level, observations we had made using our surgical model (104) suggested that it might be useful in locating the plexus, and this was the focus of our first study.

2.3 Do we regard the clavicle as a hindrance or as helpful in accessing the brachial plexus?

Incorporating the following publications, with reference numbers:


The clavicle overlies and protects the brachial plexus, but, in doing so, it obstructs our access to the plexus. The clavicle is a sigmoid-shaped bone (See Figure 4 below) that overlies the upper third of the chest wall, and connects medially to the sternum and laterally to the acromion of the scapula. The medial two-thirds are approximately triangular in cross-section, whereas the lateral third is flattened. It acts as a buttress for the shoulder joint, as well as protecting the neurovascular bundle as it descends into the arm from the neck.

At first glance, the clavicle obscures our access to the brachial plexus simply by overlying it. However, based on observations during surgical procedures for the relief of thoracic outlet obstruction at The University of Michigan Medical Center, I wondered whether the clavicle could be used to
accurately locate the plexus. This could facilitate more precise insertion of the block needle.

As the clavicle inclines posterosuperiorly in its middle third, it crosses over the neurovascular bundle as the latter courses inferolaterally across the apex of the axilla. This point of crossover defines the lateral edge of the arterial pulsation in the supraclavicular fossa.

Analysis of archival magnetic resonance images of this point of crossover raised the possibility that the parasagittal plane related to the lateral edge of the arterial pulsation in the supraclavicular fossa could be used to predict plexus and pleural depth referenced from the clavicle (See Figures 5 & 6 below).

**Figure 4: The Clavicle.**
Figure 5: Left Supraclavicular Fossa.

A. Subclavian artery
B. Clavicle
C. Trapezius m.
D. Brachial plexus
E. Sternocleidomastoid m.
F. Scapula
G. Parasagittal plane
1. 'Midpoint'
Figure 6: Magnetic Resonance Image of the Parasagittal Plane G of Figure 5.
The standard incision for the relief of thoracic outlet obstruction went through the middle of the supraclavicular fossa; hence measurement could be standardized from the edge of the skin incision.

With Ethics Approval, 20 subjects were enrolled in the study (108). People were excluded if there was a cervical rib, significant distortion of normal anatomical relationships due to soft tissue structural abnormality, or a nonstandard incision.

The preoperative measurement was taken with the patient semi-recumbent (back of bed at 40-45° elevation from the horizontal), which brought the supraclavicular fossa into a horizontal position that closely approximated that used for the surgical procedure. The most lateral point of the arterial pulsation in the supraclavicular fossa was marked. The skin over the superior surface of the clavicle was marked directly in front of this pulsation, as was the skin on the anterior border of the trapezius directly behind it. A point midway between these two points was identified as the ‘midpoint’, and was used as the reference point for all subsequent measurements. The surgical incision ran through the ‘midpoint’, from medial to lateral, across the supraclavicular fossa.

Preoperatively, the height of the ‘midpoint’ above the top and bottom of the clavicle was measured. The top of the clavicle was taken as the mark on the skin over the clavicle, while the bottom of the clavicle was palpated and then measured at this point on the skin. A small template was designed to accomplish these measurements: one edge was curved to conform approximately to the shape of the supraclavicular fossa, and another was straight and able to be aligned to be anatomically vertical. The centimetre scale ran between these two edges, so that the relevant point of contact on the skin could be followed back to the straight edge, and the vertical distance could then be read directly off the scale. This process is schematized in Figure 7 (below).

A derived figure, the ‘height of the midpoint above the middle of the clavicle’ was calculated as ‘height of midpoint above top of clavicle’ + 1/2x (‘height of midpoint above bottom of clavicle’ – ‘height of midpoint above top of clavicle’).
FIGURE 7: Schematic Drawing of Section through Parasagittal Plane G of Figure 5, with Patient Positioned Semi-recumbent.
After general anaesthesia was induced (using thiopentone 3-4 mg/kg, fentanyl 2-3 µg/kg and muscular relaxation achieved with atracurium 0.5 mg/kg), the patient was positioned semi-recumbent. Anaesthesia was maintained using nitrous oxide, oxygen, and isoflurane, with fentanyl as required. No further muscle relaxant was given during the procedure, and no padding was used behind the patient’s back or shoulder.

Intraoperatively, measurements were taken from the ‘midpoint’ on the re-approximated posterior wound edge (using a standard millimetre-scale ruler in the anatomically vertical position) to the superior surfaces of the superior trunk of the plexus, the subclavian artery, and the parietal pleura. Student’s t-test was used to compare the depth and height measurements.

Seventeen patients were included in the final analysis, with three exclusions due to non-standard incisions. There were 14 women and three men. The average age was 37±10 years, the average weight was 78±21kg, and the average height was 165±10cm.

Surgical pathology included either small muscle slips between the trunks of the plexus, encirclement of the subclavian artery by the insertion of the anterior scalene muscle, or subclavian vein thrombosis.

The preoperative measurements and derived calculations are shown in Table 1 and the intraoperative measurements are shown in Table 2.

**Table 1: Depth Estimates.**

<table>
<thead>
<tr>
<th>Height of the ‘midpoint’</th>
<th>Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Above the top of the clavicle</td>
<td>1.8+0.4cm</td>
</tr>
<tr>
<td>Above the midpoint of the clavicle</td>
<td>2.6+0.5cm</td>
</tr>
<tr>
<td>Above the bottom of the clavicle</td>
<td>3.4+0.6cm</td>
</tr>
</tbody>
</table>
TABLE 2: Actual Depths.

<table>
<thead>
<tr>
<th>Depth</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Plexus</td>
<td>1.9+0.7cm</td>
</tr>
<tr>
<td>Artery</td>
<td>3.3+0.9cm</td>
</tr>
<tr>
<td>Pleura</td>
<td>4.5+1.0cm</td>
</tr>
</tbody>
</table>

Patient weight correlated significantly with the depths of the plexus \( (P = 0.003, r^2 = 0.45) \), artery \( (P = 0.004, r^2 = 0.42) \), and pleura \( (P = 0.0003, r^2 = 0.58) \). Patient height did not correlate with these same depth measurements.

There was no significant difference between the height of the midpoint above the top of the clavicle and the depth of the plexus. There was a significant difference between the height of the midpoint above the middle of the clavicle and the depth of the plexus \( (P = 0.0007) \). There was no significant difference between the height of the midpoint above the bottom of the clavicle and the depth of the artery. Height of the midpoint above the top of the clavicle, height of the midpoint above the middle of the clavicle, and height of the midpoint above the bottom of the clavicle were all significantly different from the depth of the pleura \( (P = 0.0001, P = 0.0001, P = 0.0005, \text{ respectively}) \).

As the clavicle inclines posterosuperiorly in its middle third, it crosses over the neurovascular bundle as the latter courses inferolaterally. This point of crossover defines the lateral edge of the arterial pulsation in the supraclavicular fossa. In the parasagittal plane related to this pulsation, the anatomical relationships of the brachial plexus include the clavicle (anteriorly), the axillary artery (inferiorly), and the subcutaneous fat pad (superiorly).

The comparison of estimates of depth versus actual depth suggested that the height of the ‘midpoint’ above the top of the clavicle was useful for predicting the depth of the plexus. The weight-
related variations in depth did mean that the height of the ‘midpoint’ above the top of the clavicle tended to slightly overestimate the actual depth in the lightest patients and, conversely, slightly underestimate the actual depth in the heaviest patients.

Because all three estimates of depth were significantly different from the actual pleural depth, a needle inserted to the depth of the ‘height of the midpoint above the bottom of the clavicle’ should encounter the plexus safely. However, the pleural depth measurements did encroach within the ‘height of the midpoint above the bottom of the clavicle’ in the lightest of the cohort; therefore, the ‘height of the midpoint above the middle of the clavicle’ seemed a safer option.

Because we measured across a fat pad, differences in the distribution of body fat between the genders could have biased our result, given the predominance of women. Based on our observations, we did not believe that the supraclavicular fat pad was particularly different between the genders.

We concluded that it was possible to estimate with reasonable accuracy the depth of both the plexus and the pleura, and to use this information to safely guide the block needle to the desired neural endpoint.

This first depth gauging study raised a question about whether the same principle could be applied more laterally along the course of the plexus. This would have relevance in two respects: (i) to use for an infraclavicular approach to the plexus; and (ii) to accurately map the position of the various structures of interest across the chest wall, and hence add the further coordinate of course or direction to the already known location and depth of the plexus and pleura from this first study.

For the second study (109), we obtained Ethics Committee approval to analyse archival magnetic resonance imaging (MRI) studies which had included the upper chest wall. A representative example is shown in Figure 8. Twenty-one studies were selected on the basis of their normal infraclavicular anatomy, as judged by a radiologist.

The coracoid process (CP) of the scapula and the clavicle were used as standard reference points as they were easily identified from surface anatomy.
Figure 8: Magnetic Resonance Image View: Parasagittal Section through the Coracoid Process.

Measurements were taken in four separate parasagittal planes/positions (Figure 9):

1. through the midpoint of the CP;

2. through the medial edge of the CP;

3. one centimetre medial to the CP; and

4. the shallowest point of the infraclavicular brachial plexus (i.e. where it came closest to the skin of the anterior chest wall). This point was several centimetres medial to the CP, and was used only as an extra plane of reference because there is no surface landmark to accurately identify it. It does, however, provide invaluable information on the more medial anatomic relationships.
FIGURE 9: Right Upper Chest/Shoulder and Parasagittal Sections. (1) through centre of the coracoid process; (2) through medial edge of the coracoid process; (3) one centimetre medial to the coracoid process; and (4) shallowest point of the brachial plexus.
In each of these parasagittal planes, the following measurements were made (Figure 10):

1. horizontal distance (HD) from the skin of the anterior chest wall to the brachial plexus;
2. vertical distance (VD) from the top of the clavicle to the brachial plexus;
3. the distance, horizontally, of the centre of the brachial plexus from a vertical line down through the centre of the clavicle. (We called this the ‘divergence’: the plexus anterior to this line was a negative value, and the plexus posterior to this line was a positive value. The smaller the divergence, the more centred the plexus was underneath the clavicle, and the greater the potential for depth gauging.);
4. location of the brachial plexus relative to the CP in position 1; and
5. width of the clavicle.

**Figure 10: Measurements Pertaining to Brachial Plexus Location.**
[a] Horizontal distance from the skin of the anterior chest wall to the brachial plexus; [b] vertical distance from the top of the clavicle down to the brachial plexus; [c] distance, horizontally, of the centre of the brachial plexus from a vertical line dropped down through the centre of the clavicle (divergence); [d] location of the brachial plexus relative to the coracoid process in position 1 in Figure 9
MRI studies from eight males and 13 females were analysed. Height averaged 1.68 m (range 1.55-1.85m), and weight averaged 74 kg (52–103kg). Both HD and VD showed linear relationships ($r^2=0.97$ and $r^2=0.98$, respectively) across the infraclavicular region (See Figures 11 & 12). The VD measurements were a mathematical expression (Figure 12) of the ‘anesthetic line of Grossi’ (110). The brachial plexus passed inferior and posterior to the tip of the coracoid process.

The divergence was least in position 3 and largest in position 4. Clavicular width was greatest in positions 1-3, and least in position 4. The broader clavicle in positions 1-3, combined with the small divergence in these same positions, indicated that the plexus was centred beneath the clavicle in these positions, most exactly in position 3 (See Figure 13).

**Figure 11: HD vs. Parasagittal Plane.**
HD = horizontal distance from the skin of the anterior chest wall to the brachial plexus (graphed as mean±s.d.). The x axis, as “0” on the y axis, represents the skin of the anterior chest wall.
**Figure 12: VD vs. Parasagittal Plane.**

VD = vertical distance from the top of the clavicle to the brachial plexus (graphed as mean±s.d.). The negative scale denotes the distance below the top of the clavicle. The x-axis, as ‘0’ on the y axis, represents the top of the clavicle. Parasagittal planes: (1) through centre of the coracoid process; (2) through medial edge of the coracoid process; (3) one centimetre medial to the coracoid process; (4) shallowest point of the brachial plexus.

**Figure 13: Divergence (y-axis) vs. Parasagittal Plane (x-axis).**

Parasagittal planes: (1) through centre of the coracoid process; (2) through medial edge of the coracoid process; (3) one centimetre medial to the coracoid process; (4) shallowest point of the brachial plexus.
For these reasons, the same principal of depth gauging (Figure 14) as described in our previous study could apply infraclavicularly in position 3 (Figure 15).

**Figure 14:** The Principle of Depth Gauging.

**Figure 15:** The Practice of Depth Gauging.
The lung could be reached in some subjects in parasagittal plane/position 3, but was well behind the plexus. The lung could not be reached in parasagittal plane/position 1, through the centre of the coracoid process, as the chest wall curved around more medially.

The brachial plexus ran in a straight line (downward and backward) across the infraclavicular region of the upper chest, and passed below the inferior margin of the coracoid process. In the course of this journey, the brachial plexus lay directly inferior to the lateral third of the clavicle, the relationship being most exact one centimetre medial to the CP.

The results of this study, in combination with the first depth gauging study (108), created an accurate map of the course of the plexus across the anterolateral chest wall in relationship to the clavicle, and defined a safe zone of operation to avoid the lung. The clavicle, far from being a hindrance, was actually of benefit in accessing the brachial plexus.

There was, of course, another bone of importance – the first rib. My attention turned to the position of the first rib in relationship to changes in posture. Ultrasound was to subsequently revolutionise the approach to this structure.

2.4 ‘Unmasking’ the first rib.

In the anatomic position, the first rib lies at 60 degrees to the horizontal (Figure 16A). As the patient is positioned semi-recumbent, the first rib approximates the horizontal (Figure 16B). The skin of the supraclavicular fossa also becomes approximately horizontal in the semi-recumbent position. Therefore, in this position, a flat working surface is provided, the orientation of the first rib is known, and the chest wall drops away laterally.
FIGURE 16: The First Rib.
With ultrasound, of course, the first rib is readily visible as a dense white line across the middle of the screen when the probe is held in the root of the neck with the front edge of the probe against the lateral head of sternocleidomastoid muscle (Figure 17). Again, it is useful to have the patient semi-recumbent, but this is for ease of process. Identifying the first rib effectively leads to the nerves, as the latter are located immediately above the artery which itself is located by simply tracking along the first rib.

Given that supraclavicular techniques have referred to the first rib in the past as a backstop to prevent over-insertion of the needle without actually being able to identify its precise location (8,12,18), ultrasound has ‘unmasked’ the first rib, and thereby revolutionised regional anaesthesia in this area.

![Figure 17: Unmasking the First Rib.](image-url)
The image in Figure 16A shows the first rib in parasagittal section. My attention turned back to the coronal image in Figure 2 as it provided an opportunity to measure the position of the chest wall and the plexus, and to determine in which position the bent needle would be most closely aligned with the plexus. This was our next anatomic analysis.

2.5 An analysis of the spatial relationships of the brachial plexus using magnetic resonance imaging.

Incorporating the following publication, with reference number:


A key concept of the bent needle technique was that the needle tip could be guided tangential to the chest wall. If the needle tip could also be aligned with the plexus, there might be no medial spread of injectate with consequent avoidance of unwanted neural structures. The alignment would also facilitate catheter placement.

For these reasons, we decided to map the course of the chest wall and the brachial plexus to calculate more precisely where these alignments might occur (111).

With Ethics Review Board approval, 22 magnetic resonance imaging studies of adults, judged by an experienced radiologist to have normal supraclavicular anatomy, were retrieved from the archives. Seen on a paracoronal section, the angles made by the plexus and the chest wall to a parasagittal plane were measured (Figure 18).
There were nine males and 13 females, with an average age of 49 years (range of 27-76 years), and an average weight of 70 kg (range of 52-90kg).

The angle measurements are shown in Table 3. The plexus followed a relatively shallow course across the supraclavicular fossa, while the chest wall followed a slightly steeper gradient.
### TABLE 3: Angles made by Plexus and Chest Wall to Parasagittal Plane.

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plexus Angle</td>
<td>117°</td>
<td>105°-128°</td>
</tr>
<tr>
<td>Chest Wall Angle</td>
<td>133°</td>
<td>127°-140°</td>
</tr>
</tbody>
</table>

When these angles were compared to theoretical angles for the position of the bent needle (Figure 19), the proximal shaft of the bent needle had to be parallel or closer to the neck for the distal shaft of the needle to become aligned with the chest wall, and still closer in to the neck for the distal shaft to align with the plexus.

![Figure 19: Needle Positioning vs. Chest Wall and Plexus Angles.](image)

- (a) Bent needle in parasagittal position;
- (b) bent needle parasagittal position configured against chest wall angles;
- (c) bent needle parasagittal position configured against plexus angles;
- (d) bent needle configured for alignment with plexus angles.
To this point, the development of the technique had been one of refining the concept such that the needle placement was as precise as possible. A database was created to record an accurate profile of the technique as it was being used in clinical practice, and the following chapter details the first 572 cases.
Incorporating the following publication, with reference number:


My initial experience with the ‘bent needle’ technique was documented as a database over several years, and was ultimately published as an audit (112). The database captured demographics, indications, successes, failures, and complications. The blocks were placed either by me or by a trainee under my supervision.

For single shot anaesthesia, I bent a 22 gauge, five centimetre insulated needle (Stimuplex™, B Braun, Germany) two centimetres from its tip to an angle of 30°, with the bevel facing concave-side-in. A single bend of this magnitude was not considered to alter the mechanical properties of the needle (113). I then attached the contact wire of the needle to the negative lead of a nerve stimulator (Stimlocator™ SL3, B Braun, Germany), which was set at 0.5mA and 2Hz.

For catheter placement, I bent a 5.5cm sheathed needle (Contiplex A™, B Braun, Germany) in a similar fashion. I attached the modified needle via the pin in its rear hub to a non-bevelled drawing-up needle (B Braun, Germany), which, in turn, was attached to a luer lock extension set (Codan U.S. Corporation, U.S.A.). I then attached the negative lead of the nerve stimulator to the shaft of the drawing-up needle. These needle configurations can be seen in Figure 20 (below).

The patient was placed in a semi-recumbent position and lightly sedated (Figure 21). The skin was marked in the supraclavicular fossa approximately one centimeter behind the most lateral point of the arterial pulsation. I stood beside the patient, and after injecting the skin with local anaesthetic, the needle was inserted directly caudad. Once the bend reached the skin, further advances of the needle
were accompanied by movements to bring the hub gradually in towards the neck (having the effect of moving the needle-tip laterally). In its final position, the proximal shaft of the needle was parallel, or slightly closer, to the neck. If plexus contact occurred prior to the bend reaching the skin, the needle was still manoeuvred to achieve the desired final position. If plexus contact was not made at all, the initial direction of insertion was modified (anteriorly or posteriorly). Acceptable endpoints included both muscular twitching and paraesthesias, but more commonly the former. Twitching in the deltoide or pectoral muscular complexes was accepted for surgery affecting the proximal upper extremity, while twitching in the hand or fingers was required for the remainder of the arm. For catheter insertion, 10ml of solution was injected once the desired twitch was achieved, to spread the tissues prior to advancing the cannula off the needle and then threading the catheter through the cannula. The catheter was secured at the ten centimetre mark at the skin insertion site.

**FIGURE 20:** *Bent Needles.*
(a) For single shot anaesthesia; (b) for catheter placement.
The initial block was achieved using a mixture of 20ml of 2% lignocaine + 1:200,000 adrenalin, 2ml of 8.4% sodium bicarbonate and 8ml of sterile water. Analgesia was achieved using a bolus of 20ml of 0.25% bupivacaine + 1:400,000 adrenalin, administered six hourly as required.

For surgery at or proximal to the elbow, I used general anaesthesia in conjunction with this regional technique, unless patient preference or coexisting medical problems mandated regional anaesthesia alone. This mostly related to issues of duration of surgery and positioning.

Over a period of five years, 572 cases were performed using this technique. There were 348 males and 224 females, with an average age of 36 years (range 14-91 years) and an average weight of 89kg (range 51-176kg). All blocks were performed by me, or, on a few occasions, by trainees under my supervision. Surgical procedures included both major and minor categories throughout the territory of innervation of the brachial plexus: clavicle (10 cases); scapula (4 cases); shoulder joint (62 cases);
humerus (69 cases); elbow joint (74 cases); forearm (61 cases); wrist (163 cases); and hand and fingers (129 cases).

Based upon my model of the brachial plexus, success was measured in differing ways for anaesthesia and for analgesia. For surgical cases, anaesthesia of all seven terminal nerves of the brachial plexus had to occur for it to be judged successful; whether or not the block was adequate for surgery to proceed. Using this definition, the technique was successful in 82% of surgical cases, with ulnar sparing being most common at 7% (or just under half of the failures). General anaesthesia was required for eight cases, all of whom were among the 332 patients having surgery distal to the elbow. These patients were initially considered for regional anaesthesia alone, giving an incidence of clinical failure of 2.4%. Analgesia was measured if a catheter was placed. For analgesia to be judged successful, it had to be ‘complete’ (i.e. a pain score of zero from the outset, and throughout the time the catheter was in situ).

For those who had surgery and planned general anaesthesia (elbow and more proximal procedures), and those who had the block for analgesia without accompanying surgery, 177 of 197 interventions were successful with the first insertion (90%). There was a trend over time towards increased use of catheters for continuous postoperative analgesia, due to increased awareness of postoperative analgesic demands, particularly for surgical procedures involving bone or major muscles. Time to onset of effect was within a few minutes of injection, with failure to achieve this being an early indication of failure.

Patients were not routinely assessed radiologically for pneumothorax, but air was never aspirated through a block needle, and no one presented subsequently with symptoms of breathlessness.

Vascular puncture occurred on 30 occasions, catheter-related infection occurred twice, Horner’s syndrome occurred three times, recurrent laryngeal nerve palsy occurred once, and neuropathy lasting longer than a month occurred twice.

The bend in the needle did permit manipulation within the confines of the supraclavicular fossa to guide the needle tip into a position which made pneumothorax highly unlikely, but which facilitated catheter insertion. The clinical profile confirmed a highly versatile technique, as had been predicted by
the conceptual modeling.

There was also some evidence that the incidence of phrenic nerve paresis might be low, and this was the focus of our next study.
Incorporating the following publication, with reference number:


In the original modeling exercise for the bent needle technique, I conceptualized that the bend may take the needle tip further from the phrenic nerve, and thus lessen the likelihood of blocking it.

We determined to conduct a large series examining hemidiaphragmatic movement using ultrasound both after the initial anaesthetic block, and during continuous postoperative catheter-based analgesic management. The aim was to establish an incidence of hemidiaphragmatic paresis (HDP) with the bent needle technique. Because up to 6% of the population may have paradoxical hemidiaphragmatic movement, this was also assessed before the initial block (114). This was an international collaborative study with the leading Dutch regional anaesthesia expert Dr Rudolph Stienstra (115).

With Ethics approval, 100 American Society of Anesthesiology (ASA) I and II adult patients, who were scheduled for a variety of upper extremity surgical procedures, were enrolled in the study. The brachial plexus catheter was sited as published (112) and described in Chapter 3.

For patients undergoing shoulder surgery (Shoulder Group), an appropriate evoked twitch was in the deltoid, triceps, or brachioradialis muscles. For patients undergoing surgery distal to the shoulder (Distal to Shoulder Group), an appropriate evoked twitch was in the flexors or extensors of the fingers.

For the Shoulder Group, the block was initiated with 30ml bupivacaine 0.5% with 1:200,000 adrenalin. Additionally, the subcutaneous tissues lateral to the supraclavicular fossa were infiltrated with 10ml
bupivacaine 0.5% with 1:200,000 adrenalin to block the supraclavicular nerves which supply the skin over the shoulder and are not part of the brachial plexus.

For the Distal to Shoulder Group, the block was initiated with 30ml pH-adjusted lignocaine 1.5% with 1:300,000 adrenalin. A single peripheral nerve block (e.g. of the ulnar nerve) was permitted if the innervated territory was involved in the surgical site, and there was residual cold sensation in the cutaneous distribution of the nerve 15 minutes after the initial injection.

All Shoulder Group patients and those in the Distal to Shoulder Group undergoing surgery likely to last more than 2 hours were also given a general anaesthetic with propofol 2mg/kg, fentanyl 100µg, and isoflurane 1% in 60% nitrous oxide in oxygen by either spontaneous ventilation through a laryngeal mask airway, or controlled ventilation through an endotracheal tube.

Postoperative analgesia was provided via the brachial plexus catheter with a 20ml bolus of bupivacaine 0.25% with adrenalin 1:400,000 given 6 hourly for 24 hours, and then as requested. Patients were also given oral paracetamol 1g four times daily and oral diclofenac 75mg twice daily. No opioid analgesics were given routinely. If any of the patients who received a general anaesthetic complained of pain upon awakening at the end of surgery, the catheter was withdrawn 3cm and a further injection of 20ml bupivacaine 0.25% with adrenalin 1:400,000 was given via the brachial plexus catheter.

Success in the study was defined as follows:
Shoulder group: (1) at 60 minutes post-block insertion, ‘success’ was a decrease in cold sensation in the cutaneous distribution of the axillary nerve, difficulty abducting the arm, and a sensation of ‘heaviness’ in the arm; (2) in the recovery room, ‘success’ was a visual analog scale (VAS) score of 0/10 on awakening, or after catheter withdrawal and a further local anaesthetic top-up; (3) on the first postoperative day, ‘success’ was a VAS score = 0/10.
Distal to Shoulder Group: (1) at 60 minutes post-block insertion, ‘success’ was absence of the sensation of cold in the axillary, medial antebrachial cutaneous, lateral antebrachial cutaneous, radial, median, and
ulnar nerves, and adequate for surgery; (2) in the recovery room, ‘success’ was a VAS score = 0/10, again allowing for the possibility of catheter withdrawal and further top-up if there was initial pain; (3) on the first postoperative day, ‘success’ was defined as a VAS score = 0/10.

Any incidents of vascular puncture occurring during block insertion were recorded. All patients were examined once the block was established for evidence of sympathetic chain block (demonstrated by ipsilateral ptosis and meiosis), and ipsilateral recurrent laryngeal nerve block (demonstrated by hoarseness or weakness of the voice). Instances of tourniquet pain in those 48 patients who remained awake during their procedures were recorded. Neurological deficits were assessed once the blocks had resolved if the patient was then aware of ongoing residual numbness or weakness.

All patients underwent ultrasound examination of bilateral hemidiaphragmatic motion before and during continuous brachial plexus anaesthesia and analgesia. These examinations were performed at least three times: (i) before insertion of the brachial plexus block; (ii) after insertion of the block; and (iii) on the first day after surgery following the top-up of local anaesthetic down the catheter. The second and third ultrasound examinations were timed to occur once the brachial plexus block was present and fully effective. Patients in the Shoulder Group underwent ultrasound examination after emergence from general anaesthesia (within the first six hours after the operation). Patients in the Distal to Shoulder Group underwent ultrasound examination before induction of general anaesthesia and surgery. The ultrasound examination on the first postoperative day was performed in all patients within two hours of a bolus top-up of local anaesthetic, and block efficacy was confirmed in all patients 30 minutes prior to ultrasound examination.

The ultrasound examination was performed using an HDI 5000 ultrasound machine (ATL Ultrasound, Bothell, WA) and a curvilinear C5-2 transducer. With the patient supine, the probe was angled coronally through the lateral chest wall. Diaphragmatic movement was assessed by referencing to the superior pole of the kidney where possible, but a clear view of hemidiaphragmatic profile was obtained in all cases. Both hemidiaphragms were examined. Excursion was measured at end-inspiration,
end-expiration, and then direction of movement was assessed during a forceful sniff, looking for paradoxical motion. The ultrasonographer was blinded to technical details of the block, the radiologist reading the films was blinded to which upper extremity was blocked, and the anaesthetist was not permitted to participate in the examination.

The principal investigator was informed of any detected HDPs, and was given the task of identifying any contributory factors. Simple modifications to the study technique were permitted in this context, but they were required to be retained for the remainder of the study.

Confidence intervals were calculated for the observed incidence of phrenic nerve block. Fifty-two males and 48 females were studied, with a mean ±s.d. age of 56.5±18.6 years, and a mean ±s.d. weight of 76.1±17.1kg. Surgical procedures for the shoulder occurred on 39 occasions, and two brachial plexus catheters were placed to provide analgesia for fractures of the proximal humerus. The remaining 59 surgical procedures were performed at various sites from the mid-humerus to the fingers.

All those in the Shoulder Group who underwent surgery (39/41) experienced a preoperative decrease in cold sensation in the cutaneous distribution of the axillary nerve, had difficulty abducting their arms against gravity, and described a sensation of heaviness in the blocked arm. Thirty-six of these 39 patients (92%) emerged from general anaesthesia pain-free (i.e. VAS score = 0/10). Three of the first 14 patients treated awoke in pain (VAS score = 1-10/10). For two of these three patients, catheter retraction from ten centimetres to six centimetres at skin insertion point, with a further top-up via the brachial plexus catheter of 20ml of bupivacaine 0.25% with 1:400,000 adrenalin, produced complete analgesia. As a result of the success of this catheter retraction strategy, it was decided to place remaining catheters for the Shoulder Group at 6cm depth (25 patients). The postoperative top-ups for the Shoulder Group achieved complete analgesia in 38/39 (98%) patients. The single patient in this group who remained in pain (VAS score = 1-2/10) only required simple supplemental oral analgesia. The two patients who underwent plexus catheterization for humeral fractures achieved complete analgesia.
Those in the Distal to Shoulder Group showed blockade of all six nerves tested before surgery in 50/59 cases (85%). In six of the nine patients in whom there was nerve sparing, no further action was needed. In the other three patients, a single peripheral nerve block was performed at the level of the elbow to supplement the anaesthesia: the ulnar nerve in two patients, and the median nerve in the other. One patient required a general anaesthetic (2%). Eleven of the 59 patients were given general anaesthesia because of the anticipated length of the operation. Postoperative top-ups were fully effective in 56/59 patients (95%). In three patients, the initial block was fully effective, but the top-up via the catheter failed to achieve complete analgesia. A catheter withdrawal of three centimetres with a further top-up of 20ml 0.25% bupivacaine with 1:400,000 adrenalin achieved complete analgesia in two out of three of these patients. The third patient had residual pain (VAS score = 1-2/10), but declined additional analgesic medication.

Three patients with HDP were detected in the course of the study, out of a total of 200 scans in which a block-related phrenic nerve block could have been present (1.5%). There were 100 scans performed after block insertion. One phrenic block was detected in this group, giving an incidence of 1% (95% CI = 0-3%). There were 100 scans performed after catheter top-ups. Two phrenic nerve blocks were detected in this group, giving an incidence of 2% (95% CI = 0-4.7%). All three phrenic nerve blocks occurred in the first 43 patients studied, with an incidence of 7% (95% CI = 14.6%) for that part of the study in which modifications to technique were made. For the remaining 57 patients in the study, no phrenic nerve blocks were detected, giving an incidence of 0% (95% CI = 0-5.3%).

All three detected cases of paradoxical hemidiaphragmatic motion occurred in the Distal to Shoulder Group. The single case after block insertion occurred in a slim patient in whom the plexus was very shallow, and the needle with the bend at 2cm from the tip was difficult to manoeuvre. In subsequent patients, if the estimate of plexus depth was less than one centimeter, the needle was bent at one centimeter from the tip of the needle, resolving the problem of manoeuvrability. Approximately half of all the patients fell into this category of a shallow plexus. The first post-catheter top-up phrenic
block occurred in the context of the top-up being administered while the patient lay in a transport hammock. The hammock had the effect of squeezing the shoulders together, and we believe this in some way promoted the spread of local anaesthetic medially. When rescanned later, following top-up in a normal bed, there was no evidence of phrenic nerve palsy. The second post-catheter top-up phrenic block occurred when the catheter was placed at a depth of seven centimetres. Subsequent catheters in the Distal to Shoulder Group were placed at an insertion depth of ten centimetres.

There were no cases of Horner’s syndrome (suggesting sympathetic chain block), nor of vocal symptoms or signs (suggesting recurrent laryngeal nerve block). There were no neurological deficits detected once the blocks had resolved. There were no cases of tourniquet pain. Vascular puncture occurred in seven patients during needle insertion, but the needle was repositioned and the catheter functioned well in all seven cases.

The incidence of HDP of 1.5% in this study was lower than the incidence of HDP cited in other studies (18, 26, 28-32). A difficulty of understanding this result in relationship to other published figures is that no other study has incorporated both shoulder surgery and surgery distal to the shoulder using the same regional anaesthetic technique. It has been conventional practice to use interscalene block for shoulder surgery and supraclavicular block for surgery distal to the shoulder.

The incidence of HDP in those having shoulder surgery was 0% at block placement and 0% at catheter top up, while the incidence of HDP in those having surgery distal to the shoulder was 1.7% at block placement and 3.3% after catheter top up. These incidences compare favorably to accepted incidences of 100% HDP for single shot interscalene block (26) and 50% for continuous interscalene block (27) for shoulder surgery, and 20-80% for single shot supraclavicular block (18, 28-32) for surgery distal to the shoulder.

The blocks and catheters for the Shoulder Group were placed with different endpoints and depths of catheter placement compared to those for the Distal to Shoulder Group, and this may in some way explain the differences in incidence of HDP between those two groups.
A question remained about how this very low incidence of HDP was possible. It was not a simple matter that the point of injection was further from the phrenic nerve than with other techniques. The initial blocks for the Shoulder Group did not result in any hemidiaphragmatic pareses, but they did for the Distal to Shoulder Group. The catheters for continuous analgesia in the Shoulder Group were inserted less deeply than those for the Distal to Shoulder Group, and there were fewer phrenic nerve blocks detected.

In view of these observations, I decided to examine the hypothesis that the differences in where the needle and catheter tips were lying in the tissues were important, and in some way influenced how the local anaesthetic spread from those points. This was the basis of the next enquiry.
Chapter 5
The Axillary Tunnel

Incorporating the following publication, with reference number:


We decided to inject dye down functioning brachial plexus catheters (116) to determine if there were features which could explain the results described in Chapter 4. A number of investigators had already identified factors thought to be important to the spread of solution, including a sheath (12), the head of the humerus (98), and septae (99). Perhaps these or other factors were at work in this setting.

With Institutional Review Board approval, we selected ten patients with functioning brachial plexus catheters in situ, two of whom had bilateral catheters. Four patients had undergone shoulder surgery (Shoulder Group) and the remaining eight catheters were placed to manage pain from surgery distal to the shoulder (Distal to Shoulder Group).

The dye studies were performed on the day after surgery, between two and four hours after the administration of 20ml of 0.25% bupivacaine with 1:400,000 adrenalin via the catheter. This ensured comfort for the patients, and no distortion of the tissues from local anaesthetic at the time of dye injection.

For study purposes, a functioning catheter was defined as one associated with complete analgesia (VAS score = 0/10) and loss of cold sensation in the nerve territories of the surgical site (axillary nerve for Shoulder Group; radial, median, ulnar, medial and lateral antebrachial cutaneous nerves for Distal to Shoulder Group).

The course of each catheter, and the position of the catheter tip, was determined by injecting one millilitre of 50% diluted Omnipaque™ radiocontrast dye through the catheter, followed immediately by
computed tomography (CT) scanning at a slice thickness of three millimetres from the top of the coracoid process to the bottom of the glenohumeral joint. Twenty millilitres of 50% diluted Omnipaque™ was then injected through the catheter over 30-45 seconds, followed immediately by CT scanning at a slice thickness of three millimetres, from the top of the clavicle to 30mm below the glenohumeral joint.

The limits of spread of dye were examined and described in axial and coronal sections, and the dimensions of these limits were measured at specified levels:

1. In axial section – apex of axilla: lateral boundary of 2nd rib; lateral boundary of 3rd rib; lateral boundary of 4th rib.

In axial section, the compartment containing the dye was approximately triangular in shape. Using the geometric formula for the area of a triangle \((1/2 \times b \times h)\), where ‘\(b\)’ is base and ‘\(h\)’ is height), these measurements and calculations were made at each level: ‘\(b\)’ from the axial images, and ‘\(h\)’ from the coronal images. A unit volume was then calculated at each level based on the volume of a prism (area of triangle \(\times \text{‘l’}\), where ‘\(l\)’ = length = 1cm).

The pattern of contrast distribution relative to the catheter tip was examined, and a percentage estimate of anterograde and retrograde flow was calculated. The pattern of cross-sectional dye distribution in the axial images was noted and described.

There were six females and four males in the study, with an average age of 54±21 years, and an average weight of 80±15kg.

In the Shoulder Group, the catheter tips lay inferomedial to the medial edge of the coracoid process. In the Distal to Shoulder Group, the catheter tips were inferolateral to the medial edge of the coracoid process.

The general pattern of dye spread was up to, and contoured by, the following rigid or semirigid
structures (See Figure 22 below):

1. Superiorly: trapezius muscle, clavicle, coracoid process of scapula, subscapularis muscle, head of humerus.
2. Inferiorly: chest wall.
5. Medially: 1st rib and chest wall.

The unit volumes were as follows:

a. Apex of axilla: 5.2±1.31 cm³
b. Coracoid process – 2nd rib: 9.5±3.5 cm³
c. Subscapularis – 3rd rib: 5.22±1.76 cm³
d. Subscapularis – 4th rib: 8.0±2.0 cm³

The unit volumes (a)-(d) were significantly different to the 20cm³ volume of dye injected (p < 0.001). The unit volumes (a) and (c) were significantly different to the unit volumes (b) and (d) (p < 0.001).

In the Shoulder Group, the dye flow was on average 10% anterograde (95% C.I. = 3-17) and 90% retrograde (95% C.I. 83-97), and occurred along the posterior aspect of the plexus. There was no anterior spread to the phrenic nerve. In the Distal to Shoulder Group, the dye flow was on average 48% anterograde (95% C.I. = 34-62) and 52% retrograde (95% C.I. = 38-66), and occurred in a central distribution. The retrograde flow did not reach the phrenic nerve in these studies. These patterns are seen in Figure 23.
FIGURE 22: Boundaries of the Axillary Tunnel.

Legend
C = Clavicle
CP = Coracoid Process
CW = Chest Wall
1st R = 1st rib
G of S = Glenoid of Scapula
H = Humerus
H of H = Head of Humerus
PF = Pectoralis Fascia
S = Scapula
Ssc = Subscapularis
Our aim in this study was to better understand factors influencing the spread of injected solution prompted by the apparent clinical profile of the bent needle technique. The dye injected in the Shoulder Group spread retrogradely along the posterior aspect of the plexus, and was separate from the more anteriorly located anterior scalene muscle and associated phrenic nerve. We concluded that this pattern of flow was associated with avoidance of phrenic nerve block for the shoulder surgery patients in the earlier study. In the Distal to Shoulder Group, the dye spread retrogradely throughout the plexus to the lateral margin of the first rib, without reaching the anterior scalene muscle and phrenic nerve. There seemed to be greater potential for this flow pattern to reach the phrenic nerve on occasion. We
suggested that avoidance of the phrenic nerve in our earlier series may have been both a function of the
distance of the point of injection from the phrenic nerve, and also due to the precise placement of the
catheter within the tissue planes of the plexus.

We also observed that rigid and semi-rigid anatomic structures closely surrounded the
neurovascular bundle from the apex to the base of the anatomic axilla, creating a rigid walled
compartment, pyramidal in axial section and conical in coronal section, which we called the ‘axillary
tunnel’. Injected solution spread up to, and was contoured by, the walls of the axillary tunnel. The
spread of injectate by expansion within the tunnel was limited at any point along it: it must, therefore,
go up or down the tunnel, as determined by variations in dimension along it. There were two points at
which the unit volume of the axillary tunnel diminished significantly: (i) in the apex of the axilla; and
(ii) inferior to the coracoid process. Was it possible that these were points of resistance to flow?
The lack of anterograde flow in the Shoulder Group supported the notion of a hindrance to flow in the
subcoracoid region. In the axial views, it was apparent that the scapula/subscapularis complex lay
across the course of the plexus until the complex receded posteromedially further down the axilla
(Figure 24). The catheter tips for the Shoulder Group were placed medial to the glenoid of the scapula;
hence flow could have been influenced by the complex.

![Figure 24: Axial Images of Scapula/Subscapularis Complex.](image)
The horizontal scored line in Figures A & B is a line of reference from which to judge the
posteromedial recession of the scapula/subscapularis complex. Figure 24A is at the level of
the glenohumeral joint and the tip of the coracoid process; Figure 24B is inferior to the
glenohumeral joint.
The even distribution of flow in the Distal to Shoulder Group, together with the knowledge that the catheter tips were more laterally positioned, suggested that these catheters were located within the point of resistance. Furthermore, a catheter placed beyond the scapula/subscapularis complex (Figure 25) showed anterograde flow, but no retrograde flow.

**Figure 25: Coronal Images of Scapula/Subscapularis Complex.**

In the above images from one study subject in the Distal to Shoulder Group, the dye distribution was predominantly anterograde. Figure 25A demonstrates the catheter threading in; Figure 25B demonstrates the dye distribution distally. The tip of the catheter is seen as a dark spot in the centre of the dye, and this lies beyond the point of resistance.

On the basis of these findings, we suggested that the scapula/subscapularis complex was the cause of obstruction to flow at this level in the axilla, rather than the head of the humerus as previously suggested (98). Work published by Winnie et al. in 1964 (12) and Rodriguez et al. in 2003 (117) supported the concept that the apex of the axilla had an impact on flow patterns. Winnie et al. published radiological images which showed a restriction of spread of dye to medial to the apex of the axilla with supraclavicular block, while Rodriguez et al. published radiological images which showed restriction of spread of dye to lateral to the apex of the axilla with infraclavicular block. Neither publication commented on potential influences to the pattern of spread by the surrounding anatomy.

These anatomic findings also raised another issue, and one which had arisen in my preliminary investigations. Was the sheath of the brachial plexus, long considered a cornerstone of many regional techniques of the upper extremity, really the entity described and promoted by Winnie and others? This became the focus of my next investigation.
Incorporating the following publications, with reference numbers:


The dye studies of the brachial plexus had raised an interesting question, and one which was undoubtedly controversial. Was the sheath of the plexus a real entity or a conceptual idea? The sheath had been a fundamental tenet of regional anaesthesia of the upper extremity for many years (12, 94-96). In Winnie’s 1964 paper (12), the sheath was described as a tubular prolongation of the prevertebral fascia that created a fascia-enclosed space from the transverse processes of the cervical vertebrae to the proximal forearm. The surgical description in this project (104) of the tissues around the plexus indicated a very different quality of tissue, and one unlikely to be able to spread injected fluid in the manner we had seen. At least part of the reason for these differences might relate to the difference in anatomic models: cadaveric models make little allowance for the fact that connective tissues change their consistency rapidly after death (118).

We undertook a study which compared radiological images from patients with brachial plexus catheters to those with sciatic catheters (119), as the sciatic nerve was not regarded as being contained by such a connective tissue structure.

With Ethics Committee approval, three patients with functioning brachial plexus catheters in situ, and two patients with functioning sciatic catheters in situ, were studied. The patients with brachial
plexus catheters had undergone major wrist, elbow, or forearm surgery, and the patients with sciatic catheters had undergone major ankle surgery. For the purposes of the study, a functioning brachial plexus catheter was defined as causing absence of cold sensation in the territories of the axillary, ulnar, median, radial, and medial and lateral antebrachial cutaneous nerves one hour before the computerized axial tomography (CT) dye study. Similarly, a functioning sciatic nerve catheter was defined as causing absence of cold sensation in the territories of the common peroneal and tibial nerves one hour before the CT dye study.

Positioning of the catheter tips was determined by a radiologist by injecting 1ml of 50% diluted Omnipaque™ through each catheter, and then performing a preliminary CT scan. Twenty millilitres of 50% diluted Omnipaque™ was then injected down each catheter and a further scan performed at a slice thickness of 3mm and a pitch of 2mm. The three brachial plexus catheter scans were performed from the top of the clavicle to 30mm below the glenoid fossa, and the two sciatic catheter scans were performed from the top of the sacroiliac joints to 20mm below the lesser trochanter.

The images were then visually compared for similarities and differences. Particular attention was paid to the distribution of the dye from the catheter tip, the contours of the dye-enhanced neural tissues, and the nature of the anatomical structures immediately adjacent to the nerves. Distortion or displacement of the tissues surrounding the nerves was noted.

The brachial plexus catheter tips lay just inferolateral to the coracoid process of the scapula, and the sciatic catheter tips lay between the tip of the ischial tuberosity and the femur. Both systems showed substantial anterograde and retrograde flow from the catheter tip, with clear limits of outward flow determined by solid anatomical structures, and clear lines demarcating the limits of spread. The pattern of distribution of dye within the neural tissues was similar between the two systems, both in the region of the catheter tip and at the extremes of dye distribution. There was neither distortion nor displacement of the anatomical structures surrounding the nerves (See Figures 26-29 below). Indeed, frequently the line of dye conformed to the shape of the surrounding anatomy (See Figures 30 & 31 below).
difference between the two systems lay beyond the limits of spread of the dye, where the anatomy was clearly different (i.e. upper extremity versus lower extremity).

We believed that the similarities in the images were not coincidental. The sciatic nerve lay in a ‘tissue plane’ closely surrounded by the gluteal muscles, the ischium of the pelvis, and the femur. Similarly, the brachial plexus lay in a tissue plane closely surrounded by the clavicle, the scapula, the chest wall, and the humerus.

**Figure 26: Axial Section of Sciatic Nerve Catheter.**
**Figure 27:** Coronal Section of Sciatic Nerve Catheter.

**Figure 28:** Axial Section of Brachial Plexus Catheter.
Figure 29: Coronal Section of Brachial Plexus Catheter.

Figure 30: Coronal and Corresponding Axial Sections for Two Subjects. The white arrows indicate the dye-enhanced nerves in both coronal and axial sections. The horizontal black line in the coronal section indicates an axial section that is then displayed as directed by the solid black arrow. Note how the dye conforms to the shape of the surrounding rigid anatomy: chest wall, coracoid process, and subscapularis. Dark areas adjacent to the nerves are adipose tissue.
What is a tissue plane? It is a potential space of embryologic origin that separates muscular and/or visceral compartments, and provides space for the transmission of arteries, veins, lymphatics, and nerves between those compartments. Tissue planes were fundamental to surgical dissection technique as the zones of cleavage between different anatomic structures (120), but perhaps not sufficiently emphasized in anaesthetic practice, particularly given the number of publications in the literature that actually described them (99-101, 121-123).
There are several reasons why the tissue plane is important anatomy to understand. First, there may be minimal space for soft tissue expansion at any one point (116); therefore, flow must occur along the tissue plane according to resistances encountered along the way (116). As observed in the images from this study, one of the paths of lesser resistance within the tissue plane was along the line of the nerve (in both directions from the point of injection). The dynamics of injection had the potential to be quite different from those one might expect from a simple tubular structure such as a sheath. A series of plain X-ray film dye studies (98) had shown containment of solution, but plain X-rays do not adequately define non-bony structures, and they lack the three-dimensional perspective of computerized tomography scanning. Accordingly, it was possible to misinterpret the images from those studies, and I believe this occurred. An example is the effect of the head of the humerus on the spread of solution, shown to be incorrect in Chapter 5. Second, compartmentalisation may occur because the layers of connective tissue within the tissue plane are not homogeneous, do not necessarily interconnect, and may hinder or prevent diffusion (104). Therefore, injection at one point does not guarantee spread elsewhere. Third, it has been said that supraclavicular techniques are more effective than axillary techniques because the nerves are more compactly arranged at that location (20). This is not entirely plausible as the nerves are not far apart at either location. At the supraclavicular level, though, the neural elements reorganize significantly and their surrounding connective tissues interconnect, a feature observed when they were dissected (104). This interconnection would allow for a more even spread of injected solution, a phenomenon that was observed clinically (13). This is distinctly different at the axillary level, where the terminal nerves do not interconnect and the connective tissues surrounding them create distinct compartments for each, with limited interconnection between the compartments (99-101). Fourth, side effect profiles may be explained by the interconnection, via tissue planes, of the anatomic compartments across which the nerves traveled. Hence, an injected solution could spread to unwanted places with unwanted effects (e.g. phrenic nerve block, and interscalene or subclavian perivascular block).
We concluded that the concept of the brachial plexus sheath was an oversimplification. It ignored the important contribution made to the flow of solution by the surrounding rigid anatomy, and the effect of tissue planes within the plexus structure. There were connective tissues surrounding the nerves, but we had found them to be relatively fragile (104), and unlikely to explain on their own the flow patterns of injected solutions.

Franco et al. (124) subsequently published a paper in the journal *Regional Anesthesia & Pain Medicine* that questioned the above findings. Theirs was a cadaveric study that examined the gross anatomy of the connective tissues surrounding the brachial plexus, with the expressed intention of providing a photographic record of the sheath. Eleven embalmed cadavers and one fresh cadaver were dissected in the root of the neck, supraclavicular area and in the proximal forearm. Saline was injected into the neural structures to demonstrate swelling within the connective tissues, and methylene blue was likewise injected to demonstrate its containment within the same connective tissues. The authors demonstrated a significant connective tissue structure covering the neural structures in the root of the neck, which was in fact the prevertebral fascia representing the floor of the posterior triangle of the neck. Their axillary dissection did show dissection through a fascial layer which was the investing brachial fascia of the arm. The neurovascular bundle itself was covered by a thin layer of opaque connective tissue. This embalmed connective tissue was remarkable for its difference to equivalent tissue in a surgical dissection, which is thin and translucent.

In a letter to the editor (125), we pointed out that there was more evidence than our paper (119) to question the existence of the sheath. *Gray’s Anatomy* commented that the connective tissue surrounding the nerves rapidly changed character and diminished beyond the prevertebral fascia (126). Magnetic resonance imaging did not show it (127), and dissection in surgical patients did not demonstrate it (104).

Franco et al. responded to our letter to the editor (128) and stood firmly by all of their conclusions, but did agree that their study’s dissections had demonstrated the prevertebral fascia, and
agreed with our letter (104) which stated that ‘there is a thin layer of connective tissue which encircles and entwines the vessels and the plexus’ (p.106). Franco named this thin layer of tissue as the ‘sheath’, and confirmed that this was the structure to which Winnie referred in his 1964 paper. As an aside, others similarly had referred to this same thin layer of tissue as the ‘sheath’ (99, 100). However, in our letter (104) we had also said that ‘there is no substantive sheath, as has been suggested by some authors, who based their conclusions on cadaveric dissections. There is a thin layer of connective tissue which encircles and entwines the vessels and the plexus. It is continuous with but distinct from the prevertebral fascia. It is not of uniform consistency, but is easily divided by both sharp and blunt dissection’ (p.106). Dr Winnie’s original concept was misleading, and, indeed, had been challenged and modified on multiple occasions (98-102).

More recently, the literature has described the paraneural sheath of the sciatic nerve, based on gross anatomic specimens, microscopic analysis (129), and ultrasonic identification (130). Does this negate our conclusion that the brachial plexus sheath was more conceptual than real, as the comparator in our study (119) was the sciatic nerve? I believe not, and consider that there may be some misunderstanding among other authors (129, 130) about the dynamic effects of the surrounding tissues in these circumstances. Anderson and colleagues (129) described the tissue layer surrounding the sciatic nerve as a ‘thin, transparent, and fragile’ (p.411) tissue layer, which is identical in meaning to our words when we described the tissues around the brachial plexus as a ‘thin layer of connective tissue ....’ (104). It is unlikely that this thin layer of connective tissue has the structural integrity to contain the bolus of fluid and spread it in the manner demonstrated because of its very fragility. The volumes injected are far greater than the unit volumes of the neural/neurovascular bundles at any one point. I suggest that the effects seen are those of counter-pressure from the surrounding semirigid and rigid tissues, and tracking of the fluid occurs along the tissue planes according to resistances encountered along the way. Thus, I reach the same conclusion – the concept of a sheath is an oversimplification because it ignores the important contribution made to flow of solution by the surrounding rigid anatomy, and the effect of
tissue planes within neural structures. There are connective tissues surrounding nerves, but we had found them to be relatively fragile (104), and unlikely to explain, on their own, the flow patterns of injected solutions.

I started the detailed analysis of the anatomy of the axilla and its application to the bent needle technique (described in the foregoing chapters) prior to the introduction of ultrasound in regional anaesthesia. Following the introduction of this new technology, the project has evolved to embrace ultrasound. The advantage of visualizing anatomic structures in the supraclavicular area was clear, and the challenge was to use the anatomic insights and clinical findings described in the foregoing chapters in this context. These issues will form the focus of the next chapter.
CHAPTER 7

Incorporating and Converting to Ultrasound

Ultrasound was introduced to clinical practice across the time span of this project. Its usefulness in visualising anatomic structures and tracking needle insertion is now well-established. There are a number of ways in which the anatomic analysis and block technique of this project can be incorporated with ultrasound use.

7.1 I believe surface landmarks to be of great use in conjunction with ultrasound

With the introduction of ultrasound, it was suggested that landmark-based techniques were too unreliable to justify ongoing use. It is, in my opinion, a shame to discard the valuable information that some of those landmarks provided, and the analysis of the relationship of the clavicle to the plexus discussed in Chapter 2 demonstrates that point.

My goal has been to link surface landmarks with anatomy visualized on ultrasound, as illustrated in the following four examples. Examples 1-3 are general applications of this linkage while Example 4 introduces this linkage as it relates specifically to the project technique.

Examples

1. The use of patient positioning to orientate to the first rib, and the ‘unmasking’ of the first rib using ultrasound, was described in Chapter 2. The lateral head of sternocleidomastoid muscle, as a reliable surface anatomic structure, can also be used to further help locate the first rib using ultrasound. Placing the ultrasound probe along the base of the neck on the medial side of the supraclavicular fossa with the anterior end of the probe against the lateral head of sternocleidomastoid muscle and oriented very slightly medially to give an oblique parasagittal view of the root of the neck, shows the first rib as a bright white line across the middle of the screen, as described in Chapter 2. Tracking along the first rib leads to the
subclavian artery, and the nerves are visible above and behind the artery. Put simply, the lateral head of sternocleidomastoid muscle leads to the first rib, which leads to the subclavian artery, which, in turn, leads to the nerves (See Figure 17 above).

2. The coracoid process of the scapula is a reliably palpated anatomic surface landmark. The plexus is known to pass immediately inferior to the coracoid process, immediately deep to the pectoral muscles and is accompanied by the axillary artery (109), as described in Chapter 2. Placement of the top of the vertically orientated ultrasound probe adjacent to the coracoid process reveals the pectoral muscles and, deep to these, the pulsating axillary artery. The nerves surround the axillary artery. The coracoid process is a guide to the pectoral muscles, which lead to the axillary artery, which leads to the nerves.

3. The supraclavicular fossa is a readily identifiable surface landmark, and from the depth gauging study on plexus depth (108) described in Chapter 2, we know that the floor of the fossa, formed by the chest wall, is three to four centimetres deep. Prior to scanning the area, the depth setting can be preset at four centimetres, which is most likely to bring all structures of interest within the image. The same study (108) indicated that the plexus depth will be two to three centimetres, which will therefore place the plexus in the middle of the screen. From the same data set, we know that in very slender people the structures will be shallower, and in the obese they will be deeper. Depth adjustments can, therefore, be predicted.

4. The clavicle, the lateral head of the sternocleidomastoid muscle, and the supraclavicular fossa are all surface landmarks relevant to the conversion of the bent needle technique to an ultrasound-guided technique, and the way they link to the ultrasound image is described in detail below.
Knowing about the hazards that you can’t see on the screen

Incorporating the following publication, with reference number:


The limitations of ultrasound must be understood for it to be effective and safe. One of these is range of view. The sonographic image is two-dimensional and only provides anatomic information on those structures which appear within the ultrasound beam. Anatomic structures of importance outside the beam are, therefore, potentially at risk. Many images of supraclavicular anatomy describe the lung as being below the first rib, and indicate that the risk of pneumothorax is controlled by avoiding insertion of the needle in that area. However, there is also risk of pneumothorax medial to the sonographic image (See Figure 32 below): the dome of the lung is the immediate medial relation of the first rib; therefore, during an approach to the nerves along the first rib, the needle tip needs to be kept clearly in view to avoid this ‘unseen’ danger (107).

7.3 I revisit the original concept of the bent needle technique and convert to ultrasound-guidance

Incorporating the following publication, with reference number:


In the original description of the bent needle technique (112) described in Chapter 3, the basic concept was to guide the needle tip into a tangent to the chest wall to minimise the risk of pneumothorax. The tangent ran medial to lateral from the neck to the arm, across the lateral chest wall.
FIGURE 32: Ultrasound-Guided Supraclavicular Block.

A – Needle introduced;
B – Local anaesthetic injected;
C – ‘Chimney effect’;
D – Axial CT scan at level of block.

Unlabelled arrows in images A, B & C indicate needles.
Arrow heads in images A, B & C indicate nerves.

If this same tangent is rotated to pass across the anterolateral chest wall, it will run from the lateral edge of the sternocleidomastoid muscle obliquely down behind the clavicle through the supraclavicular fat pad to the plexus. This tangential line can be followed with a needle under direct vision using ultrasound from skin to plexus. The anatomic analyses from Chapters 2, 5 and the earlier part of this chapter suggest that this to be done with great accuracy, with precise knowledge of the location of the apex of the lung and chest wall to minimize (or eliminate) the risk of pneumothorax, with knowledge of the anatomic relationships and depths of structures to permit optimization of the
sonographic image prior to needle insertion, and with precise placement of the needle tip for maximum clinical advantage.

When the ultrasound probe is placed to image the line of tangent down behind the clavicle, with the medial end of the probe abutting the lateral head of the sternocleidomastoid muscle (Figure 33), the image achieved shows an ovoid artery, and behind it an elongated area of white with translucent circles within it (Figure 34 & 35). This is an oblique view of the neurovascular bundle. The elongated area is the tissue plane of the brachial plexus, surrounded by fat and omohyoid muscle superficially, the chest wall inferiorly, the first rib medially (not visible on the screen), the clavicle anteriorly, and the scapula and related musculature posteriorly. Due to the combined appearance of the artery and the elongated area resembling a comet and its tail, I nicknamed this view of the brachial plexus the ‘comet tail’. The target for the block needle is within the comet tail (Figure 35).

Figure 33: Ultrasound Probe in Position in the Right Supraclavicular Fossa for Ultrasound-Guided Axillary Tunnel Block.
Figure 34: Ultrasound Image of Artery and Target Area.

Figure 35: The ‘Comet Tail’.
Artery (heavy dash line), target area or ‘comet tail’ (heavy solid line), chest wall (light dash line). The needle is introduced from the top left of the screen, as per the arrow.
There is another important aspect to this view of the brachial plexus. One of the findings from our study describing the axillary tunnel (116) was that fluid (either dye or local anaesthetic) injected into the tissue planes of the plexus posterior to the artery did not reach the anteriorly situated phrenic nerve. We believed that this finding explained the absence of hemidiaphragmatic paresis in the 39 study patients who underwent regional blocks for shoulder surgery in our study which examined the incidence of hemidiaphragmatic paresis using the bent needle technique (115). It is this same part of the brachial plexus which is being visualized as the comet tail.

This view of the plexus is just outside the lateral border of the first rib (Figure 36), which situates it more laterally than a technique such as ‘eight ball corner pocket’ (132) which is situated over the first rib. While there would seem to be little physical distance between the ‘comet tail’ block and these other supraclavicular techniques, the lower incidence of phrenic nerve block when injecting into this area (115) confirms that there is a difference.

I believe there are two anatomic reasons to explain this difference. First, the comet tail represents the posterior part of the tissue planes of the brachial plexus, and injection here results in spread along the posterior aspect of the plexus, as explained above. Second, the comet tail is within the apical point of resistance, which is formed by the clavicle, scapula, and first rib (116). This affects the spread of injected fluid (Figure 37), with flow to either side of the point of resistance in the same way as was described for the subcoracoid point of resistance in Chapter 5. Because the needle tip is positioned at division level of the brachial plexus, spread also occurs to the cords (laterally) and the trunks (medially). It is possible that this medial-lateral division of flow also contributed to avoidance of the phrenic nerve, as described above.
FIGURE 36: ‘Comet Tail’ Block.
Showing distribution of 2ml radiocontrast dye with needle positioned for placement of ultrasound-guided axillary tunnel block.
FIGURE 37: Dye Distribution Following Subsequent Injection of 20ml Local Anaesthetic.
CHAPTER 8
Conclusion

This project originated with the goal of trying to minimize the risk of pneumothorax, a complication widely regarded as the critical factor in discouraging use of supraclavicular block. Using geometric principles, a strategy was developed which initially required an adaptation of the needle to accommodate to the anatomy. A bend in the needle also facilitated catheter placement, and the clinical experience broadened use of the technique from that usually associated with supraclavicular techniques to include surgical procedures on the shoulder, clavicle, and scapula. The versatility of the technique became a key advantage.

The initial detailed analysis of the applied anatomy of the axilla allowed me to accurately map the course of the brachial plexus across the anterolateral chest wall, and to locate the brachial plexus in relation to the clavicle and the axillary artery. The apparent obstruction of the clavicle in accessing the brachial plexus was removed.

Ultimately, a combination of anatomic analysis and a reconfiguring of the original design concept led me to convert the bent needle technique to an ultrasound-guided technique. One of the advantages of the conversion to ultrasound was the ability to follow the line of tangent in plane from the skin to the plexus.

The absence of phrenic nerve block when the local anaesthetic was injected posterior to the artery, as detailed in Chapters 4 & 5, makes this technique unique among supraclavicular and interscalene techniques. It would, therefore, appear to be safe for use in those with limited respiratory reserve requiring shoulder surgery. Certainly, this has been my clinical experience.

The dye distribution patterns of ultrasound-guided axillary tunnel block differ from those of supraclavicular and infraclavicular block (12, 117). The placement of the needle tip within the apical point of resistance means that the injected solution spreads proximally and distally to the point of
injection. Given that the point of injection occurs at division level in the plexus, the ensuing spread is to the trunks and cords, respectively. Ultrasound-guided axillary tunnel block is, therefore, a divisions/trunks/cords block, in contrast to supraclavicular (trunks/nerve roots) or infraclavicular (cords) blocks as discussed in Chapter 2.

Anatomic and mathematical science has underpinned this project, with live dissection, computerized tomography, and magnetic resonance imaging providing important perspectives. Our findings have challenged the traditional understanding of the anatomy. We do not believe that the concept of the brachial plexus sheath accurately portrays the actual anatomy. The effect of the surrounding rigid/semirigid tissues has hitherto been largely ignored, but is, in fact, of great importance. The dynamics of injection of fluid into the tissues are such that the traditional terminology is misleading. The assumptions and conclusions of where and how fluid spread occurred were found to be, in large part, incorrect. Together, the studies presented here show that it is possible to have a single technique that achieves reliable block of all seven terminal nerves of the arm and with a significantly altered side effect profile, but this has required a new understanding of the dynamics of the anatomy.

While it was suggested in Chapter 2 that a potential advantage of the bent needle technique might be a reduced chance of needle-related nerve damage due to closer alignment of the needle bevel with the plexus, this is unproven by this body of work and must remain theoretical. One of the difficulties of proving such an hypothesis relates to the low incidence of needle-related nerve injury, and the large numbers that would, therefore, be required in a randomized controlled trial. Indeed, for this reason, it is unlikely that any particular strategy will ever be proven safer in this regard.

Safety would seem though to be a multifactorial process. Anatomic knowledge, ultrasound guidance, low current nerve stimulation, and adrenalin-free solutions may all be components of a package to enhance safety.

This body of work does not include a randomized controlled trial (RCT). This relates in part to the development of the model as a study in applied anatomy, and, subsequently, to the transformation of
the technique to ultrasound-guidance. I believe that the background anatomic and mathematical science does stand firmly as a scientific basis for the technique, but I concede that without an RCT it is unlikely that ultrasound-guided axillary tunnel block will supersede interscalene block as the technique of choice for shoulder surgery. The study hypothesis would need careful consideration as powering for incidence of phrenic nerve block requires far smaller numbers than powering for efficacy.

There is another aspect to the discussion of axillary tunnel block versus interscalene block for shoulder surgery. The concern over complications associated with interscalene block was covered in Chapter 1, Section 3.3. The search for a safer alternative has veered towards supraclavicular block, which would, in fact, represent a major shift in practice: the separation point between the techniques for shoulder versus more distal targets has always occurred, albeit incorrectly, between supraclavicular and interscalene blocks. I believe that ultrasound-guided axillary tunnel block provides a solution. This body of work has shown it to be effective for shoulder surgery. By bypassing the interscalene space, the complications associated with the vertebral artery and central neuraxial structures are not a part of its profile. Proof for this hypothesis requires an RCT to establish non-inferiority in terms of efficacy, and this is a source of ongoing interest and research.

I entitled this thesis ‘Supraclavicular Regional Anaesthesia Revisited’, with the intention of redesigning supraclavicular block to improve its safety profile. As the body of work progressed, however, my understanding of the anatomy and the dynamics of injected solutions within those anatomic compartments evolved. The result of this investigation has been a deeper understanding of both the anatomy, and the developed technique. Revisiting supraclavicular block has resulted in ultrasound-guided axillary tunnel block, which is not a supraclavicular technique either by its needle tip placement, spread characteristics, or clinical profile.

Future directions for research might include dose and volume alteration studies, the effect on block efficacy of altering axillary tunnel dimensions with clavicular movement, and comparative studies with the traditional block approaches. These studies could all help to improve our understanding
of ultrasound-guided axillary tunnel block, and better place all of the upper extremity regional anaesthetic techniques in terms of their clinical utility and safety.

In Chapter 2, I explored the concept of whether the clavicle was a hindrance or a benefit in locating and accessing the brachial plexus, and our investigations concluded that it could be helpful. Subsequent investigations, described in Chapters 4, 5 and 7, also demonstrated that the clavicle has a key role in determining spread characteristics as a component of the axillary tunnel, and that this could be specifically targeted for clinical and side effect profile advantage.

Ultrasound-guided axillary tunnel block changes the approach by acknowledging the relationship of the clavicle to the brachial plexus, and using it to advantage. It is, therefore, an important additional regional anaesthetic technique of the upper extremity.
APPENDIX 1
Awards


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3. Invited Speaker, Brachial Plexus Workshop, University of Michigan Medical Centre, Ann Arbor, Michigan, USA, March 1995.


8. 1st World Congress on Regional Anaesthesia & Pain Medicine, Barcelona, Spain, May 2002.

10. ESRA Athens 2004:
   i. Cornish PB, Leaper C, Nelson G, Anstis F, McQuillan C, Stienstra R. Can Phrenic Nerve Paresis Be Consistently Avoided During Continuous Supraclavicular Regional Anaesthesia?
   v. Cornish PB: The ‘Sheath’ of the Brachial Plexus – Fact or Fiction?

11. The Axillary Tunnel – Redefining the Limits and Dynamics of Brachial Plexus Blockade.


APPENDIX 3
Journal Publications

12. Cornish PB. The ‘sheath vs. ‘the axillary tunnel’ – a conflict of states and understanding. Reg
18. Cornish PB. ‘A catastrophic complication’ certainly – but has the cause been correctly identified? Anaesthesia 2012.
APPENDIX 4
Published Abstracts


APPENDIX 5

Other Publications


36. Ediale KR, Myung CR, Neuman GG. Prolonged hemidiaphragmatic paralysis following


45. Riazi S, Carmichael N, Awad I, Holtby RM, McCartney CJ. Effect of local anaesthetic volume (20 vs. 5 ml) on the efficacy and respiratory consequences of ultrasound-guided interscalene brachial plexus block.


67. Selander D, Mansson LG, Karlsson L, Svanvik J. Adrenergic vasoconstriction in peripheral nerves


78. Vucković I, Dilberović F, Kulenović A, Divanović KA, Voljevica A, Kapur E. Injection pressure as


90. Uppal V, Sondekoppam RV, Ganapathy S. Permanent diaphragm paralysis after shoulder rotator...
cuff repair: interscalene block is not the only factor. Anesthesiology 2014; 120: 1054-6.


92. Christopher A. DiMeo, MD; Andrew Cameron, MBChB; Christopher Cook, DO; Victor Zayas, MD; Dorothy Marcello, BA. Supraclavicular vs. Interscalene Brachial Plexus Block for Shoulder Surgery. Reg Anesth Pain Med 2010; 35: 460.


