Forearm Compartment Syndrome: Anatomical Analysis of Surgical Approaches to the Deep Space

Daniel N. Ronel, M.D., Estomih Mtui, M.D., and William B. Nolan, III, M.D.

Forearm compartment syndrome is a surgical emergency that usually requires release of the superficial muscle compartments. In some clinical situations it is imperative to also explore the deep muscle compartments. There are no anatomical guides for surgical exploration of the deep compartments that would minimize collateral damage to surrounding vessels, nerves, and muscles. Surgical injury in the setting of ischemia, especially vascular injury, compounds the tissue damage that has already occurred. The authors evaluated four surgical approaches (three volar and one dorsal) to the deep forearm by performing detailed anatomical dissections on 10 embalmed and plastinated cadavers. They used a scoring system to rate the approaches for their ability to visualize the deep space without causing iatrogenic injury to superficial muscles, arteries, and nerves. In the volar forearm, an ulnar approach to the deep space is simple, causes the least iatrogenic surgical injury, and provides access to the deep volar forearm structures. The plane of dissection is between the flexor carpi ulnaris and the flexor digitorum superficialis. Dividing one or two distal segmental branches of the ulnar artery to the distal flexor digitorum superficialis exposes the pronator quadratus. Lifting the ulnar neurovascular bundle with the flexor digitorum superficialis in the middle third of the forearm exposes the flexor digitorum profundus and the flexor pollicis longus. This approach to the deep space requires no sharp dissection. In the dorsal forearm, a midline approach between the extensor digitorum communis and the extensor carpi radialis brevis is simple and safe. (Plast. Reconstr. Surg. 114: 697, 2004.)

The treatment of compartment syndrome requires expedient fasciotomy when nonoperative maneuvers such as cast removal are unsuccessful.1-3 If left untreated, elevated tissue pressure within the fascial confines decreases capillary blood perfusion below a level necessary for soft-tissue viability.4 Most patients ultimately have minimal limb dysfunction when fasciotomy has been performed promptly and to an adequate depth. Postoperative loss of function may be caused by several factors, including damage from the initial injury, ischemia caused by elevated tissue pressure before fasciotomy, inadequate fasciotomy, and iatrogenic surgical injury.

The forearm is divided into multiple fascial compartments, each containing several muscles that are additionally enclosed within individual epimysial envelopes. Three forearm compartments are usually described: the volar, dorsal, and the lateral (mobile wad) compartments. The interosseous membrane separates the volar and dorsal compartments from each other, and the posteriorly and radially located lateral compartment is demarcated by a connective tissue septum from the antebrachial fascia.5 In most cases of compartment syndrome, the volar muscles are the most severely affected, followed in severity by the muscles of the dorsal compartment and the lateral compartment.4 Some communication exists among the three main compartments, and release of the volar compartment often relieves elevated tissue pressure in the dorsal compartment. Intraoperative pressure measurements and clinical findings may preclude the need for a separate dorsal fasciotomy to relieve this extensor...
compartment. The lateral compartment musculature is superficial and easily decompressed. Within the volar compartment, additional distinction can be made between the superficial and deep muscles. The superficial muscles include the pronator teres, palmaris longus, flexor digitorum superficialis, flexor carpi radialis, and the flexor carpi ulnaris. The deep muscles include the flexor digitorum profundus, flexor pollicis longus, and the pronator quadratus. The flexor digitorum profundus and flexor pollicis longus are particularly vulnerable in compartment syndrome, as they may be compressed against rigid bone and the unyielding interosseous membrane. Anatomical and clinical reports demonstrate that release of the superficial volar compartments may not be adequate to relieve deep pressures in these muscles. Some authors even consider the pronator quadratus to lie within an additional compartment in the distal forearm, as elevated tissue pressures can affect it independently from the other forearm muscles.

The dorsal compartment is also divided into superficial and deep muscles. The extensor digitorum communis, extensor carpi ulnaris, and the extensor digiti minimi are the superficial group, which lie in a plane above the deeper abductor pollicis longus, extensor pollicis brevis, extensor pollicis longus, extensor indicis, and the supinator.

Mandatory exploration of deep muscle compartments is indicated in situations where the deep muscles are preferentially injured, such as in cases of high-voltage electrical injury. The high electrical resistance of bone transmits a significant thermal injury to the adjacent muscles of the deep compartment. Other conditions that require exploration of the deep spaces include severe crush injuries, situations involving extended pressure on the forearm, such as an unconscious patient lying on his or her forearm, and when there is ongoing sepsis or suspicion of necrotic muscle, despite previous fasciotomy. If epimysiotomies of the deep muscles are not performed in these situations, necrosis and contracture may result.

Three standard approaches to the deep forearm have been described in the medical literature, in the context of fractures or nerve compression. These ulnar, central, and radial approaches were depicted by McConnell, Henry, Thompson, and Spinner and were subsequently modified by many authors. The approaches do not attempt to minimize iatrogenic trauma to small arteries because they are not described in the setting of forearm ischemia. In Henry’s approach to the anterior radius, for example, the recurrent radial vessels are ligated. Decreasing the blood supply to an ischemic muscle in the context of compartment syndrome could be significantly injurious.

A rational surgical approach to the deep space in the setting of forearm compartment syndrome has not been described. Such an approach must provide access to the pronator quadratus, the flexor pollicis longus, and the flexor digitorum profundus while minimizing iatrogenic trauma. Anatomical textbooks do not delineate the dominant vascular pedicles within the deep space in enough detail to plan a safe surgical approach. The goal of this study was to investigate the ability of various surgical approaches to visualize the deep muscles of the forearm without causing iatrogenic injury to muscles, nerves, and arteries.

**Methods**

We reviewed the published literature on forearm anatomy, surgical approaches to the forearm, and compartment syndrome. The results of our literature review were collated and categorized. Two of the authors, working together, dissected 10 adult cadaver arms of various ages and race. Eight of the arms were embalmed. Two of the arms were fresh specimens: these were injected with red silicone and then mildly plastinated (Ronald Wade, University of Maryland). Records of each step of the dissections were made using digital photography. The photographs were archived and categorized on a database for subsequent retrieval and analysis. Radial, central, and ulnar approaches were followed to access the deep muscles of the volar forearm. Only one approach was followed to access the deep space of the dorsal forearm. The number of arteries, nerves, and superficial muscles that were encountered during the approaches was recorded.

In the radial approach, the skin incision was made radial to the midline of the volar forearm, starting at the proximal wrist crease and extending to the antecubital fossa. The superficial fascia was released and the dissection continued radial to the flexor carpi radialis and between the flexor carpi radialis and the flexor digitorum superficialis. In the central approach, the skin incision was made over the center of the volar forearm. The superficial fascia was released and the deep dissection...
continued either radial or ulnar to the palmaris longus and then between tendons of the flexor digitorum superficialis. In the ulnar approach, the skin incision was made radial to the flexor carpi ulnaris at the wrist and extended to the medial epicondyle of the humerus. The superficial fascia was released and the dissection continued radial to the flexor carpi ulnaris, between the flexor carpi ulnaris and the flexor digitorum superficialis. In the dorsal forearm approach, the incision was made in the midline and the superficial fascia released. The distal interval between the extensor digitorum communis and the extensor carpi radialis brevis was followed proximally.

We developed a scoring system to measure the difficulty of deep muscle exposure (Table I). The system has three elements: assessment of iatrogenic muscle injury, of iatrogenic nerve injury, and of iatrogenic arterial injury. Each element was scored on a scale of 1 to 3, with 1 being the best (the least damage was caused by the surgical approach) and 3 being the worst (the most damage was caused by the surgical approach). In the category of muscle injury, the surgical approach scored 1 if there was no muscle injury, 2 if sharp dissection of muscle was required to access the deep space, and 3 if the division of a superficial muscle was required. In the category of arterial injury, the surgical approach scored 1 if no arterial branches were divided, 2 if fewer than 50 percent of the segmental branches to any muscle were divided, and 3 if more than 50 percent of the segmental branches to any muscle or if a dominant pedicle was divided. In the category of nerve injury, the surgical approach scored 1 if no dissection around a motor nerve was required, 2 if dissection around a motor nerve was required, and 3 if division of a motor nerve was required.

Data for surgical approaches to the volar forearm were collected for each specimen. The average score for each approach was calculated (Table II). We hypothesized that there is a superior surgical approach to the deep compartment of the volar forearm: this was tested using the Mann-Whitney U test for nonparametric data. Only one approach to the deep compartment of the dorsal forearm was tested because it consistently yielded the lowest possible score, demonstrating its efficacy and safety. No other dorsal approaches were tested because it would be impossible to improve the results.

**RESULTS**

Each surgical approach easily allowed the release of the superficial volar compartment. In the radial approach, the flexor digitorum superficialis impeded access to the deeper forearm in all the specimens. Division of the origin of the flexor digitorum superficialis III was necessary to evaluate the flexor pollicis longus and flexor digitorum profundus muscles (Fig. 1, left). Segmental branches from the radial artery to the flexor digitorum superficialis were required in seven of 10 specimens (Fig. 2, left). Dissection through and around the flexor digitorum superficialis was adjacent to motor nerve branches from the median nerve in six of 10 specimens (Fig. 2, right). There was no significant injury to motor nerves.

In the central approach, it was consistently difficult to separate the proximal fibrous raphe of the palmaris longus from the flexor carpi radialis or the flexor carpi ulnaris. Sharp dissection of the raphe or division of the flexor digitorum superficialis was required to reach the flexor pollicis longus and flexor digitorum profundus. The division of several arterial branches from the ulnar artery to the flexor digitorum superficialis was required in seven of 10 specimens (Fig. 2, left). Dissection through and around the flexor digitorum superficialis was adjacent to motor nerve branches from the median nerve in six of 10 specimens (Fig. 2, right).

In the ulnar approach, the pronator quadratus was best approached in a plane between the ulnar artery and the flexor digitorum superficialis in the distal forearm. One or two distal segmental arterial branches from the ulnar artery to the flexor digitorum superficialis and/or the flexor carpi radialis were required division in five of 10 specimens (Fig. 3, left). As the
dissection moved proximally, the remainder of the deep compartment could easily be seen if the ulnar neurovascular bundle was raised with the flexor digitorum superficialis (Fig. 3, right).

This approach spared all proximal segmental branches to the flexor carpi radialis and flexor digitorum superficialis. In two specimens, one segmental branch to the distal flexor carpi ulnaris was preserved. The deep approach was used in all cases with no recurrent compartment syndrome or major complications.

TABLE II

Volar Forearm Surgical Approach Data

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<tr>
<th></th>
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Approach R, radial; approach C, central; approach U, ulnar.

Fig. 1. Radial approach. (Left) Grade 3 muscle injury: access to the deep space requires division of the flexor digitorum superficialis (FDS). (Right) Grade 2 arterial injury: branches from the radial artery to the flexor carpi radialis (FCR) impede deep exploration.

Fig. 2. Central approach. (Left) Grade 3 muscle injury and grade 2 arterial injury: there is no plane in the proximal flexor digitorum superficialis (FDS), it is difficult to separate the flexor carpi radialis or flexor carpi ulnaris from the palmaris, and ulnar artery branches to the flexor digitorum superficialis impede deep access. (Right) Grade 2 nerve injury: sharp dissection around median nerve branches to the flexor digitorum superficialis is required.
naris was divided. No dissection of superficial muscles or motor branches was required with the ulnar approach.

Using our scoring system to assess the safety of each surgical approach, the lowest possible score, which corresponds to the safest possible approach, is 3. The highest possible score, which corresponds to the most injurious surgical approach, is 9 (Table III). The average radial approach score was 6.1 (SD, 0.32), the average central approach score was 5.8 (SD, 0.63), and the average ulnar approach score was 4.0 (SD, 1.05). The dorsal approach score was 3.0 in all the cadavers. Using the Mann-Whitney U test for nonparametric data ($U = 5.8656$), the ulnar approach caused significantly less surgical trauma than the radial approach ($p < 0.001$, $z = 4.0701$) or the central approach ($p < 0.003$, $z = 3.4349$).

**DISCUSSION**

Forearm compartment syndrome requires immediate evaluation and treatment. The need for operation is established by careful review of the patient’s history, the presence of physical signs and symptoms such as pain with passive stretching, paresthesias, paresis, and palpably tense compartments, and, if needed, the measurement of elevated compartment pressures.

Limited incisions to minimize collateral morbidity from fasciotomy do not offer access to all components of the forearm and increase the potential for missing an ischemic or necrotic muscle group. A commonly used approach, described by McConnell in 1920 and modified by Gelberman, begins 1 cm proximal and 2 cm lateral to the medial epicondyle. It is carried obliquely across the antecubital fossa and over the volar aspect of the mobile wad and is then curved medially to reach the midline of the forearm at the junction of its middle and distal thirds. The incision is continued straight distally to the proximal wrist crease ulnar to the tendon of the palmaris longus and is finally curved across to the mid-palm. The subcutaneous tissues are divided to expose the deep fascia, and individual muscles are mobilized for examination. If the muscles of the dorsal compartment require release after the volar fasciotomy, a straight longitudinal incision is made below the lateral epicondyle toward the midline of the wrist. Other incisions described for the treatment of compartment syndrome criss-cross the forearm or gently sweep across it in various directions (Fig. 4). Incisions that cross the forearm will transect more of the venous and lymphatic return than will a straight incision, and the resolution of forearm edema could be impaired. Such incisions may also prevent the future design of a radial fore-

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<tr>
<th>Approach</th>
<th>Average Score</th>
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<tr>
<td>Radial</td>
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<tr>
<td>Central</td>
<td>5.80</td>
<td>0.63</td>
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<td>Ulnar</td>
<td>4.00</td>
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Table III: Comparison of Surgical Approaches

Lowest possible score (safest approach) = 3; highest possible score (least safe approach) = 9.
arm flap, as the vascular supply and outflow of the skin pedicle would be compromised.

Most cases of forearm compartment syndrome are adequately treated by release of the superficial volar compartment, regardless of which surgical approach is chosen. Those clinical situations that mandate exploration of the deep volar or dorsal compartments, however, require a significant understanding of forearm anatomy to follow a surgical approach that will minimize further injury. Clinical examples include high-voltage electrical injury, severe crush injuries, extended extrinsic forearm pressure (such as an unconscious patient lying on his or her forearm), and ongoing evidence of myonecrosis or sepsis despite previous superficial fasciotomy. In some cases, even after compartment fasciotomy, the epimysium of individual muscles must be incised to relieve persistently elevated tissue pressure.\textsuperscript{20,21} This can only be achieved with adequate visualization of the deep space.

**Arterial Clinical Anatomy**

The arterial anatomy of the upper extremity is varied and often does not correlate with descriptions in standard anatomical textbooks.\textsuperscript{22,23} The blood supply to the deep forearm muscles is discussed in the studies of Parry and Mathes, whose results indicate that the muscles are likely vascularized at their proximal ends (Table IV). Their studies were focused on the creation of forearm flaps.\textsuperscript{24,25} A more complete understanding of forearm muscle blood supply that is applicable to the treatment of compartment syndrome and that avoids damaging dominant pedicles or a criti-

### Table IV

Arterial Supply of Forearm Muscles

<table>
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<th>Compartment</th>
<th>Muscle</th>
<th>Arterial Supply</th>
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<td>Mobile wad</td>
<td>Brachioradialis</td>
<td>Radial recurrent</td>
<td>Segmental, 5 pedicles</td>
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<td>Radial recurrent</td>
<td>Dominant</td>
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<td></td>
<td>ECRL</td>
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<td>Dominant</td>
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<tr>
<td>Dorsal</td>
<td>Supinator</td>
<td>Posterior ulnar recurrent</td>
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</tr>
<tr>
<td></td>
<td>Radial recurrent</td>
<td>Posterior interosseous</td>
<td>–</td>
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<tr>
<td></td>
<td>EDC</td>
<td>Posterior interosseous</td>
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<td>EDM</td>
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<tr>
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<td>ECU</td>
<td>Posterior interosseous</td>
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<td>EPL</td>
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<td>Superficial volar</td>
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<td></td>
<td>Palmaris longus</td>
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<tr>
<td></td>
<td>PQ</td>
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ECRB, extensor carpi radialis brevis; ECRL, extensor carpi radialis longus; EDC, extensor digitorum communis; EDM, extensor digiti minimi; ECU, extensor carpi ulnaris; APL, abductor pollicis longus; EPB, extensor pollicis brevis; EPL, extensor pollicis longus; EIP, extensor indicis proprius; FDS, flexor digitorum superficialis; FCR, flexor carpi radialis; FCU, flexor carpi ulnaris; FDP, flexor digitorum profundus; FPL, flexor pollicis longus; PQ, pronator quadratus.

The number of segmental pedicles in muscles that are already ischemic is needed.

As it lies on the deep surface of the flexor digitorum superficialis, the ulnar artery gives off a posterior recurrent branch that supplies the flexor carpi ulnaris with a dominant pedicle. Near the middle of the forearm the ulnar artery gives off a medial common interosseous branch, which immediately branches into the anterior and posterior interosseous arteries. The anterior interosseous artery travels on the interosseous membrane with the anterior interosseous branch of the median nerve between the edges of the flexor digitorum profundus and flexor pollicis longus. This small artery gives off several critical branches to the muscles of the deep volar compartment. At the proximal edge of the pronator quadratus the anterior interosseous artery passes through the interosseous membrane to join the palmar carpal network of vessels. The particular sensitivity of the deep volar muscles (pronator quadratus, flexor digitorum profundus, and flexor pollicis longus) to elevated tissue pressure can be understood in the context of Poiseuille’s law and the small anterior interosseous artery supplying the muscles:

$$q = \frac{\pi r^4 \Delta P}{8 \mu L},$$

where $q$ is blood flow through the artery, $r$ is the artery radius, $\Delta P$ is the change in pressure across the artery, $L$ is the length of the artery, and $\mu$ is the viscosity. Compressive forces in compartment syndrome narrow the already small diameter of the anterior interosseous artery, reducing blood flow significantly more than in the larger and more superficial arteries.

After having given off the common interosseous branch, the ulnar artery travels with the ulnar nerve down the forearm just radial and deep to the belly of the flexor carpi ulnaris, and gives off one or two distal minor pedicles from its ulnar side. In our ulnar approach, we divided one or two of these minor distal branches to the flexor carpi ulnaris to visualize the deep compartment in two of our specimens. We also noted five to seven branches from the ulnar artery to the flexor digitorum superficialis. The most distal one or two of these may have to be sacrificed in the ulnar approach we describe, and raising the ulnar neurovascular bundle with the flexor digitorum superficialis spares the remainder of the segmental branches to the flexor digitorum superficialis and flexor carpi radialis.

The radial artery gives off a radial recurrent artery branch close to its origin, which supplies the brachioradialis, extensor carpi radialis brevis, and extensor carpi radialis longus. Approximately 3 cm distal to the bifurcation a branch from the radial artery supplies the flexor carpi radialis, although the muscle receives most of its blood supply from six distal segmental pedicles of the radial artery. These are the branches that must be divided in the radial approach we used to access the deep space.

Analysis of the arterial supply to the forearm reveals that each compartment has one or more muscles that are supplied by a dominant pedicle. In the lateral compartment, the mobile wad, the radial recurrent artery supplies the extensor carpi radialis brevis and extensor carpi radialis longus, and in the dorsal compartment, the posterior interosseous artery is the dominant pedicle for the extensor indicis and perhaps the extensor digitorum communis. In the superficial volar compartment, the flexor digitorum superficialis and flexor carpi ulnaris are supplied by a dominant pedicle from the ulnar and posterior ulnar recurrent arteries, respectively, and in the deep volar compartment, the anterior interosseous artery is the dominant pedicle for the pronator quadratus, flexor pollicis longus, and flexor digitorum profundus. These relatively small yet important dominant branches may be overlooked during emergent decompression procedures, and their transection could contribute to muscle ischemia.

Nerve Clinical Anatomy

Muscle swelling may trap the median and ulnar nerves during their course in the forearm, and any forearm incision should provide access to these nerves. The common anatomic sites of compression should be evaluated during forearm fasciotomy if there is preoperative evidence of neuropathy or if weakness or paresthesias cannot be elicited in the uncooperative patient.

The median nerve gives off the anterior interosseous nerve to innervate all the deep muscles except a variable portion of the ulnar half of the flexor digitorum profundus. The median nerve accompanies the anterior interosseous artery on top of the interosseous membrane between the flexor pollicis longus and
flexor digitorum profundus. There are four anatomic regions of potential median nerve compression: the lacertus fibrosus (the wide bicipital aponeurosis), the proximal edge of the pronator teres between the muscle’s humeral and ulnar heads, the proximal edge of the flexor digitorum superficialis, and the carpal tunnel.\(^1\)\(^,\)\(^14\) Release of the superficial fascia decompresses the pronator teres and flexor digitorum superficialis muscles. Although the fibrous arch of the flexor digitorum superficialis should not be in a contracted state in the acute setting of compartment syndrome, if exposure of the arch is required, opening the fibrous raphe between the flexor carpi radialis and pronator teres or the raphe between the flexor carpi radialis and flexor digitorum superficialis will give good exposure. Sharp dissection is required for both of these approaches. It is our preference to use the flexor carpi radialis/flexor digitorum superficialis interval, thereby maintaining a straight incision and avoiding extension to the radial side of the forearm across cutaneous nerves and veins.

Release of the carpal tunnel in isolated forearm compartment syndrome is controversial; there are no reports of compartment syndrome causing carpal tunnel syndrome, and an anatomical study of compartment syndrome revealed that elevated forearm tissue pressures were not transmitted to the carpal tunnel.\(^26\)

The anatomical site of ulnar nerve compression in the forearm is the fibrous origin of the flexor carpi ulnaris. The ulnar approach we describe is directly over this fascia. The antebrachial cutaneous forearm nerves are variable in their position and may be necessarily compromised by fasciotomy incisions. Any longitudinal or oblique incision on the forearm will cross some branches of the cutaneous nerves; fortunately, much of the forearm skin innervation is redundant. Reasonable care must be exercised regardless of the skin incision.

The various levels of injury described in our scoring system were determined from an experimental, anatomical perspective rather than from a clinical standpoint to compare surgical approaches in the laboratory. It would be ideal, but difficult, to translate the relative weight of each specific iatrogenic injury to a clinical outcome to determine its reliability and validity.

Compartment syndrome can occur in the context of injuries that require treatment by an approach other than the ulnar one described here. For example, a radial approach is usually required for internal fixation of the radius and may involve planned iatrogenic injury to the origin of the flexor digitorum superficialis. In such a case, the approach for forearm decompression is dictated by the underlying injury.

**Conclusions**

In our dissections, an ulnar approach to the deep space of the volar forearm in a plane between the flexor carpi ulnaris and the flexor digitorum superficialis caused the least amount of iatrogenic injury to superficial muscles, arteries, and nerves. The incision is similar to that described by Matsen et al.,\(^2\) which extended from the medial epicondyle to the flexor crease of the wrist. The incision we tested curves gently midline toward the ante-cubital fossa in the proximal third of the forearm. The superficial compartment along the radial side of the flexor carpi ulnaris is opened distally, which reveals the ulnar neurovascular bundle. The flexor carpi ulnaris is retracted ulnarly, and a plane underneath the flexor digitorum superficialis can be appreciated. As the flexor digitorum superficialis is retracted upward, the median nerve should remain attached to the undersurface of the muscle, radial to its deep belly. The pronator quadratus can be seen distally between the ulnar neurovascular bundle and the flexor digitorum superficialis; one or two branches from the ulnar artery to the flexor digitorum superficialis may need to be ligated to release the pronator quadratus. Moving proximally, the ulnar neurovascular bundle is raised with the flexor digitorum superficialis to preserve its branches to that muscle. A branch from the ulnar artery to the flexor carpi ulnaris may need to be ligated. Raising the flexor digitorum superficialis in the middle third of the forearm allows easy access to the remaining muscles of the deep volar compartment, the flexor pollicis longus and the flexor digitorum profundus. Exposure of the three deep muscles allows their evaluation for ischemia and, if needed, individual epimysiotomy. On the dorsal forearm, the standard midline approach can be safely carried deeply between the extensor digitorum communis and the extensor carpi radialis brevis.

The ulnar approach to the deep space between the flexor carpi ulnaris and the flexor digitorum superficialis appears to be a superior surgical approach to the deep muscles of the volar forearm. It avoids damage to the dominant blood supply within each forearm com-
partment. The other surgical approaches increase the risk of iatrogenic injury. Additional cadaver dissections will strengthen our conclusions and may elucidate other nuances specific to each surgical approach. A clinical outcome study comparing the different paths to the deep space in compartment syndrome would be difficult to perform, and although none of the approaches is claimed to be clinically superior, the ulnar approach makes the most anatomical and logical sense.

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