From the Battlefront: Peripheral Nerve Surgery in Modern Day Warfare

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• Nerve injury • Gunshot wound • Prosthesis

Care of peripheral nerve injuries has been challenging military surgeons for centuries. British surgeons followed the nihilistic pattern of the times, recommending no treatment for divided nerves during the Napoleonic wars.[1] During the U.S. Civil War, Mitchell and colleagues[2] observed functional recovery of injured limbs but attributed it to the overlap from adjacent nerve innervations. In World War I, 3129 peripheral nerve injuries were recorded in the U.S. Armed Forces alone.[3] This incidence provided opportunities to compare several techniques of nerve repair, and many important conclusions on the repair of peripheral nerve injuries were published throughout the 1920s and 1930s.[4]

In World War II, 25,000 peripheral nerve injuries were evaluated by the Army Medical Corps. In 1944, a peripheral nerve registry was ordered by the Surgeon General of the U.S. Army; and in 1956, Woodhall and Beebe[5] published a study entitled "Peripheral Nerve Regeneration: A Follow-Up study of 3,656 World War II Injuries." The British also had a large experience with treating these injuries at multiple sites, including more than 2500 cases treated at Oxford.[6,7]

One of the largest modern series was published by clinicians at the Belgrade Military Medical Academy, where 3091 missile-induced peripheral nerve injuries were managed from 1991 to 1995. In several articles, Roganovic and colleagues[8–12] report functional outcomes on the repairs of 119 tibial, 157 peroneal, 128 ulnar, 81 median, and 131 radial nerves. The surgical results in the civilian population are also well categorized by several other experienced authors, including many large series by Dr. David Kline and colleagues.[13–21] The techniques for surgical management of blunt and sharp penetrating wounds in the military population are the same as those described for similar wounds in the civilian population.

Most military peripheral nerve injuries result from high-velocity gunshot wounds or fragments from explosions, resulting in blunt nerve injuries. Initial treatment is frequently performed by orthopedists or general surgeons, and attention is focused on stabilizing fractures, debriding necrotic tissue, repairing vascular damage, and preventing infection. Because of the extensive soft tissue damage frequently present, these wounds will often require multiple washouts. When identified, the status of injured nerves should be documented. Any nerve stumps should be tacked down to prevent retraction, and reconstructed in the ensuing weeks.

To guide surgical management, patients who have neuromas in continuity should be followed up clinically and elecrodiagnostically over the next several months to assess for evidence of spontaneous recovery. Indications, techniques with intraoperative nerve action potential recordings, and timing of exploration are well covered elsewhere, and do not differ from those presented in civilian

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literature. Also similar to the civilian literature, outcomes are related to the nerve and level of injury, timing of the repair, length of the nerve defect, and health of the surrounding tissue and vascular bed.

Pain is a common manifestation of peripheral nerve injury. A meta-analysis of the literature for "causalgia" published in 2003 found that high-velocity missile injuries accounted for 77% of reported cases.[22] In 2006, Roganovic and Mandic-Gajic[23,24] categorized missile-induced peripheral nerve injury into four different types of pain syndromes: deafferentation pain, neuropathic pain, complex regional pain syndrome type II (CRPS-II), and reinnervation pain. Of 2239 patients available for follow-up, 326 (14.6%) had a clinically significant pain syndrome; this represented 2652 (12.3%) of the prospectively assessed nerve injuries. Of these 326 patients, 258 (79.1%) underwent surgical exploration.

The United States and its allies have been treating casualties from the global war on terrorism since 2001. Since the onset of hostilities in October 2001 through January 2005, 1566 U.S. Service Members sustained 6609 combat wounds, according to the Joint Theater Trauma Registry. This figure does not include soldiers killed in action, returned to duty within 72 hours, or non–battle-related injuries. Distribution of these wounds included 29.4% head and neck, 5.6% thoracic, 10.7% abdominal, and 54.1% extremity. The extremity percentage is consistent with previous conflicts, whereas the head and neck percentage is higher. The mechanism of injury was 81% explosion and 19% gunshot, which varies from the historical explosion percentage of 65% to 73% between World War II and Vietnam.[25] The extremity injuries were evenly distributed between the upper and lower extremities: 129 (4%) were amputations, 915 (26%) were fractures, 1881 (53%) were soft tissue wounds, and 144 (4%) were nerve injuries.[26]

Publications reporting data from previous conflicts typically lag 10 to 20 years behind while data are collected, analyzed, and eventually published. Publications are sparse on peripheral nerve injuries from the current conflict (the War on Terrorism). This paucity can be explained by the relatively short interval since the onset of the conflict, the fact that the casualties are still being received, and the wide distribution of rehabilitative care at centers throughout the country, which impedes efficient follow-up data collection efforts. Publications are expected to emerge over the next 5 to 10 years, which will better evaluate the long-term results of current therapy and treatment strategies.

Approximately 90% of the casualties evacuated back to the United States from the global war on terrorism undergo their initial stateside treatment at either Walter Reed Army Medical Center or National Naval Medical Center. Before the conflict, a multidisciplinary peripheral nerve clinic, including orthopedics, physical medicine and rehabilitation, neurosurgery, and neurology, was established under the leadership of Dr. Neal Naff. This clinic still operates and has provided evaluation and treatment for a large number of casualties who had peripheral nerve injuries over the years. The number of patients who had any pain syndrome, including CRPS, has been extremely low. For the previously noted reasons, exact numbers are not yet tabulated and published; however, in the authors' 2-year experience in this clinic, only one surgical exploration was required to treat neuropathic pain.

This apparent reduction in missile-related casualties is commonly attributed to the aggressive early use of advanced regional anesthesia. Since 2003, Dr. Chip Buckenmeir has championed the use of regional anesthesia in combat casualties.[27] Previously used in a limited form in Vietnam,[28] this technique calls for early intervention on the battlefield and during evacuation, using peripheral nerve blocks, continuous-infusion peripheral nerve catheters, and patient-controlled anesthesia when appropriate for patients who have injured limbs. These techniques have been used on 70% of combat amputees and 57% of a reported series of 500 battle-related extremity injuries that underwent surgery at Walter Reed Army Medical Center between March 2003 and December 2004.[29] Peripheral nerve catheter infusions are gradually tapered over several days to weeks, often transitioning to opiates, which are more gradually tapered. Tricyclic antidepressants, nonsteroidal anti-inflammatory medications, and anticonvulsants are also used liberally. Although more rigorous outcome data will need to be analyzed and published from this strategy, applying pain control with advanced regional anesthesia may markedly reduce the incidence of pain syndromes from blast- or missile-induced peripheral nerve injury.

Regardless of mechanism or location of a peripheral nerve injury, pain-free functional restoration remains the primary goal. The results of primary nerve grafting for motor and sensory functional restoration is well documented in many outstanding monographs, and remains dependent on the location of the injury, timing of the repair, and need for a graft. Much attention has recently focused on blast injury as it relates to traumatic brain injury, and research efforts are ongoing to better define the response of the brain to overpressure, electromagnetic pulse, and other less-studied components of a blast. No current clinical evidence suggests that peripheral nerve injuries sustained as a result of blast have a worse recovery potential than those sustained by a gunshot wound; however, it is an intriguing concept and may warrant further investigation.

Functional results of nerve repair procedures are often suboptimal. The Defense Advanced Research Program Agency has launched an extensive program designed to improve functional restoration for upper-extremity amputees that may have implications for peripheral nerve surgery in the future. This program has two components: development of a fully functional artificial upper extremity, and further development of the neural–machine interface to obtain complete integrated control of this advanced prosthesis. Amazing progress has been made in both areas. The current limb developed for the program has an 8-lb grip capability, 10-lb wrist capability, 20-lb elbow capability, 9° of freedom, receptors for 2-point discrimination up to 2 mm at the fingertips, pressure sensation at 0.25 N, temperature differentiation up to 10°F, and proprioceptive capability up to 10°. The next-generation arm will have 21° of freedom, full range of motion with proportional tactile receptors, and cosmetic appearance undifferentiated from human skin and form.

The neural–machine interface component of the project is more complex. Significant successes have already been reported with indirect neural control. At Northwestern University, Kuiken and colleagues[30] used a technique called *targeted reinnervation* to allow a patient who had high upper-extremity amputation to control a prosthetic limb. In this patient, neural transfers were performed from the ulnar, median, musculocutaneous, and radial nerves to motor nerves supplying different parts of the pectoralis major or serratus anterior. Two sensory branches were coapted end-to side into the median and ulnar nerves. Reenervation was allowed to occur and then computer analysis was used to translate muscle firing in the pectoralis region into artificial arm movement. Sensory feedback was provided by thumping the pectoralis, which had been reinnervated by ulnar and median afferents.[30]

Work is progressing in the development of electrode arrays for implantation into injured peripheral nerves above an injury site, where afferent and efferent impulses may be captured or delivered through wireless interaction with a distal robotic limb using computer technology. To accomplish truly fine dexterous control of finger movement, most researchers believe the interface will need to more directly connect with the motor and sensory cortex of the brain.

Early experiments have already provided proof of concept. A primate model has learned to perform simple tasks with a robotic arm using a direct cerebral cortex interface. More sophisticated work is ongoing for individual finger actuation using this type of neural–machine interface. The ultimate goal is the creation of a completely integrated, totally functional prosthetic limb. Although this research is being conducted with amputees in mind, these artificial limbs may eventually provide a functional restoration superior to what can be obtained with direct nerve repair techniques. This may eventually alter the approach to patients who have a severely impaired limb from peripheral nerve injury. If replacing affected limbs can provide more robust functional improvement with an acceptable complication profile, patients may choose amputation over direct nerve repair in some cases.

Throughout history, warfare has led to several medical advances. Management of peripheral nerve injury has similarly developed as a result of experience with treating combat wounds. The current conflict is also providing opportunities for medical refinements to improve the care and understanding of disease. The initial impression is that a reduced incidence of pain syndromes is present in casualties who have peripheral nerve injuries as a result of more aggressive early pain control using advanced regional anesthesia techniques, but long-term outcome studies must still be completed to validate this observation. Functional restoration using a new generation of advanced prosthetic devices may soon exceed that which can be obtained through biologic repair of nerve tissue.

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