Presented in part as an invited talk at the University of Brescia, Italy, 2007, and as an I-Pod interview for the American Association of Neuromuscular and Electrodiagnostic Medicine, 2008.

Critical illness has come to mean sepsis and multiple organ failure. Sepsis, which is due to invading organisms or severe trauma, provokes a systemic inflammatory response syndrome leading to septic shock and organ dysfunction. Sepsis occurs in two percent of hospitalized patients and utilizes 25 percent of Intensive Care Unit (ICU) beds. Mortality rates exceed 20 percent. Sepsis is evident in most patients who, while receiving mechanical ventilation and intravascular lines, are in the ICU for more than one week.

It is now known that the nervous system, like other organs, is afflicted in these critically ill patients. Septic encephalopathy causes stupor or coma. Critical illness polyneuropathy, myopathy, or a combination of both, causes difficulty weaning from mechanical ventilation and limb weakness. These nervous system complications occur in up to 70 percent of critically ill patients. All are reversible if the critical illness can be successfully treated, possible in at least half the cases.

As workers in the ICUs struggle to overcome these widespread effects, the nervous system complications are overlooked or misdiagnosed. Stupor may be attributed to sedation, weaning difficulties to diaphragmatic fatigue, and limb weakness to catabolic myopathy. With successful weaning the patient is discharged to a general ward. Here the patient may still show mental confusion. There is difficulty dressing, eating, rising from a bed or toilet seat, standing, and walking. Shortness of breath and fatigue is evident. Unless further investigated, the nature of these symptoms remains unexplained, and a puzzle to the patient, family, and caregiver.

Fortunately, intensivists are now tackling the problem. Intensive Care Unit patients are being taken off sedation at regular intervals to test their level of consciousness so that the level of sedation can be more accurately determined. At this time, limb strength can be assessed. If weakness increases electrophysiological, and in some instances, muscle biopsy procedures are performed. The presence of critical illness polyneuropathy, critical illness myopathy, or both can be accurately identified, greatly aiding long-term management and attempts at prognosis.

Thirty years ago, when I and my colleagues in the Department of Clinical Neurological Sciences at Victoria Hospital, London, Ontario, Canada, began to consult on neurological problems in the ICU the above conditions were little known. A series of investigations were conducted that did much to illuminate their nature and bring them to the attention of the medical community.

The following is a personal account, a memoir, of these investigations.

Critical Illness Polyneuropathy

In the 1970s, Victoria Hospital, University of Western Ontario, London, was one of Canada’s oldest teaching hospitals. It had been named as part of the Queen Victoria jubilee celebrations in 1897. The portrait of the good queen still hangs
in the entrance (Figure 1). The hospital had a busy Emergency department and a crowded operating room schedule. The large 30-bed general and medical ICU was quickly developing an international reputation, notably for its investigation of sepsis and septic shock.

In 1977, while I was Chief of Clinical Neurological Sciences at Victoria Hospital and Director of the EMG laboratory, William Sibbald, Director of the ICU, asked me to investigate a 56-year-old woman. Sibbald had trained for three months in our neurology service and he and his staff readily asked for neurological consultations. The woman had been in the ICU for three weeks but could not be weaned from the ventilator. I knew an EMG would be necessary and so Sibbald arranged for the patient to be transferred to our EMG laboratory since we did not have a portable EMG system at that time. The patient was attached to a ventilator and was receiving intravascular lines. Intensive Care Unit nurses were in constant attendance during this time. In the laboratory I obtained the history, mainly from reviewing the hospital chart and speaking to the ICU nurses, but briefly questioning the patient, who answered with nods and head shakes. At this point the patient was alert although had previously been confused. A reasonably complete neurological assessment was achieved.

She had been admitted to the ICU with severe pneumonia due to *Staphylococcus aureus* and *Klebsiella pneumonia*, complicated by lactic acidosis, dehydration, and transient renal failure. She had required endotracheal intubation, mechanical ventilation, and management in the ICU. Cephalolithin sodium and gentamyacin had been prescribed.

I noted neck, chest wall, abdomen, and limb muscles were very weak. Tendon reflexes were absent. Position sense and vibration sense were distally impaired, but pinprick was preserved. The electrophysiological studies indicated severe axonal degeneration of motor and sensory fibers (Figure 2).

Possible causes of an axonal polyneuropathy were negative: cerebrospinal fluid examination, blood levels of antibiotics, urinary porphyrins, acute and chronic convalescent serum for Influenza A & B, adenovirus, psycosis, mycoplasma pneumonia, respiratory syncitial virus, mumps, herpes simplex, and varicella viruses, tissue culture and animal anoculation of the cerebrospinal fluid, serum thyroxine, phosphate and magnesium, creatine phosphokinase, and B12. The serum albumin and blood lymphocyte counts were reduced.

She was treated with total parental nutrition and gradual recovery occurred. She left the hospital in a wheelchair at four and a half months. At six months, strength was improved. Tendon reflexes were still absent but vibration sense and position sense were now normal. Repeat EMG studies confirmed the improvement (Figure 3). At two year follow-up, she could walk independently but had residual signs of polyneuropathy.

During the next four years, three more patients with similar findings were observed. The fifth patient was a 29-year-old male...
who presented with severe head trauma. At 14 days his limbs were first noted to be flaccid and immobile. Persisting infection prevented transfer to the EMG laboratory and a neurological consultation was not performed. At three months, he died of a cardiac arrest following an emergency cholecystectomy.

This fifth patient was presented at Victoria Hospital Neurological Sciences Grand Rounds. Comprehensive autopsy studies of both the central and peripheral nervous system were performed by Joseph Gilbert, Director of Neuropathology. Multiple samples of nerve and muscle, trunk, proximal and distal limbs, were examined. These studies revealed a severe, distal, axonal degeneration of motor and sensory fibers with resulting denervation atrophy of muscle. The distal nature of neuropathy was emphasized by the normal appearance of the spinal cord (except for chromatolysis of anterior horn cells), and of motor and sensory nerve roots. It is likely autopsies of ICU patients in other institutions had failed to identify critical illness polyneuropathy because only brain, spinal cord and nerve roots were examined, not the distal nerves and muscles.

I immediately recalled the four earlier patients; two of these had also died and had come to autopsy revealing similar findings. Angelika Hahn, my colleague in neuromuscular disease, and a former research fellow, and I had puzzled over the nature of these polyneuropathies. All had in common severe sepsis and multiple organ failure, termed critical illness by intensivists.

We presented our findings at several national and international meetings where there was little interest. No one, to my knowledge, attended some of the poster sessions. Neuromuscular experts thought these were simply examples of Guillain-Barré syndrome. The editor of The Annals of Internal Medicine rejected our first paper documenting these five patients, wondering why the cerebrospinal fluid protein was so low in patients who obviously had Guillain-Barré syndrome? He wondered if our laboratory was in error in testing for protein. Finally Dr. David Marsden, editor of the Journal of Neurology, Neurosurgery and Psychiatry, accepted the paper and it was published in 1984.5

We began to look for similar patients in the ICU. We soon observed 15. These were compared to 16 with Guillain-Barré syndrome observed during the same period. Guillain-Barré syndrome was often preceded by a minor infection or inoculation with a latent period of days or weeks before its onset. “Critical ill polyneuropathy” as we called it at that time, developed during the course of the critical illness. Guillain-Barré syndrome was a demyelinating polyneuropathy while critically ill polyneuropathy was of a primarily axonal nature.6

However, during this period we did observe five patients who had an unusually severe axonal polyneuropathy, but who otherwise had all the features of Guillain-Barré syndrome. Tom Feasby was the lead author of the paper reporting these patients.
The condition has since been recognized as acute motor and sensory axonal neuropathy (AMSAN), a variant of Guillain-Barré syndrome. Electrophysiological studies were essential in identifying these polyneuropathies since clinical signs in half the cases were equivocal. By 1983, 19 patients had been collected. Douglas Zochodne, neuromuscular research fellow, agreed to review the extensive clinical records.

The electrophysiological features again confirmed the primary axonal degeneration of motor and sensory fibers. Comprehensive morphological studies at autopsy in nine patients, and superficial and deep peroneal, and sural nerve biopsy in two patients mirrored the electrophysiological features. To detect the earliest changes in nerve, the techniques of semi-thin sections and teased fiber preparations were utilized. There was denervation atrophy of type I and type II fibers. Necrosis and ultrastructural changes in muscle in four patients suggested primary involvement of muscle. Phrenic nerve conduction studies, and morphological studies of phrenic nerves and diaphragm, explained the respiratory insufficiency and difficulty in weaning from mechanical ventilation.

P.K. Thomas, editor of *Brain*, readily accepted the manuscript but indicated instead of “Critically Ill Polyneuropathy” the correct term should be “Critical Illness Polyneuropathy”. I sent Thomas’ letter to the heads of the Departments of English and Journalism at the University of Western Ontario. Both agreed with Thomas. I wrote Thomas, “P.K., I should know better than to correct an Englishman about his own language”. Thomas responded, “Yes Charlie, but I am Welsh, not English” (Ouch!!).

Before our research of the 19 cases began, I had met with George Wells, statistician at the University of Western Ontario. We assembled a protocol for the chart review, but one that could also be applied to a prospective study that we were planning. Norbert Witt, neuromuscular fellow, carefully conducted this prospective study. The results were published in the journal *Chest* in 1991.

We took into account certain important factors in the analysis of these 49 patients. In the past, interpretation of electrophysiological studies had centered on measurements of conduction velocity, but in primary axonal degeneration these are only mildly affected. The main affect is on the amplitudes of the compound muscle and sensory nerve action potentials. This was apparent to me in my earlier investigations of uremic neuropathy. More accurate electrophysiological methods needed to be developed to identify abnormality in an individual.

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**Figure 4:** Evidence of neuromuscular dysfunction in the early stages of sepsis, at its onset, upper two traces, and three weeks later, lower two traces. Note the marked decline in amplitude, but also the increase in duration, to a similar degree on both proximal and distal stimulation of the median nerve, recording from the thenar muscle. These changes suggested primary dysfunction of the muscle fiber membrane.

**Figure 5:** Pasteur with his wife who helped him in his research.
patient and significant changes in follow-up. The fact that advancing age reduced these amplitudes was well known. However, our research showed that reduced limb temperature and smaller limb girth in females increased these amplitudes. These factors were accommodated in the statistical analysis. We also used a composite score combining all electrophysiological results from each patient into a value, a percentage of normal, which we termed “peripheral nerve function index”. This index was used in the statistical analysis to determine which of a wide variety of factors could have been responsible for the reduced peripheral nerve function. Only three proved statistically significant: time in the ICU, reduced serum albumin and elevated blood sugar. All were well-known markers of sepsis. The results of our studies provided no traditional cause for a primary axonal degeneration such as B vitamin deficiencies, antibiotic toxicity, etc.

These studies further confirmed our suspicion that sepsis was at the basis of the nervous system complication. Here was a condition, critical illness, with widespread, potentially devastating affects. Could the entire nervous system be affected with the other organs?

We had evidence of the affects on the peripheral nervous system, but what about the central nervous system? Again the evidence was strong. All patients with critical illness polyneuropathy had acquired an encephalopathy of varying severities before their polyneuropathy became evident. Septic encephalopathy had been recognized and there had been animal studies to try and determine its nature. However, there had been no documentation of the clinical, electrophysiological and morphological features in humans. These were to be disclosed by Jackson, resident in neurology, and Bryan Young, my colleague and Director of the Electroencephalography laboratory. Young had then, and continues to have a great interest in encephalopathies in the ICU.

Sibbald asked me to present our findings at a three-day conference in Florida attended by North American experts in sepsis and septic shock. Our contention that septic encephalopathy and critical illness polyneuropathy were due to sepsis and septic shock were readily accepted by the intensivists, and I gained, at this meeting, new insights into possible basic mechanisms.

Could muscle as well as brain and peripheral nerve also be affected? Until our observations, muscle weakness in the ICU had been attributed to a catabolic myopathy, and difficulty in weaning, to diaphragmatic fatigue. While muscle weakness could readily be explained by the polyneuropathy, I had observed myopathic appearing units on needle EMG and Gilbert, Hahn and Zochodne had observed necrosis and ultra-structural changes of muscle suggesting features of a primary myopathy. Moreover, on analyzing images of the compound muscle action potentials, I had observed that while the amplitude dropped in the early stages of sepsis, there was also an increase in the duration. This distinctive appearance could not be explained by denervation, but was due to primary dysfunction of the muscle fiber membrane.

Zochodne pursued the muscle problem. P31 nuclear magnetic resonance spectroscopy revealed in patients who were not septic, but had generalized denervation of forearm muscles due to disuse atrophy, a marked depletion of bioenergetic reserves. But there was an even greater depletion in two patients who had had a severe critical illness polyneuropathy and myopathy.

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Thus bioenergetic failure might also explain the reduced amplitude and increased duration of the compound muscle action potentials.

In the 1970s, about the same time we were observing our cases of critical illness polyneuropathy, others were observing myopathies of various designations, most frequently called “acute quadriplegic myopathy”.21 Initially these cases were not clearly linked to critical illness. However, Op de Coul, a Dutch neurologist and an early pioneer of neurocritical care, suggested nerve and muscle were together affected, a “critical illness polyneuromyopathy”.22 More recent studies have solidified the relation of the myopathy to sepsis. Lacomis and colleagues have defined the entity of critical illness myopathy.23 Electrophysiologically it is often characterized by inexcitability of muscle membranes on direct muscle stimulation, first identified by Rich and colleagues in Philadelphia.24 It has a variety of morphological features, notably myosin deficiency, less frequently muscle necrosis. However, in a few cases muscle necrosis may be quite severe, a condition identified by Erbshloß in 1955 observed a polyneuropathy following anoxic coma after shock or cardiac arrest. In 1961, Mertens31 described “coma polyneuropathies” in patients who had circulatory shock associated with acute intoxication and severe metabolic crisis, seemingly due to metabolic and ischemic lesions of the peripheral nervous system. In 1971 Henderson et al32 described a polyneuropathy in patients with burns. Four septic patients developed a severe polyneuropathy in 1977, which Bischoff et al33 attributed to gentamycin sulfate.

While there has been doubt in some circles about the relationship of critical illness polyneuropathy and critical illness myopathy to sepsis, the relationship appears now to be established. In the recent systematic review by Stevens et al34 at Johns Hopkins, USA, 1421 patients were evaluated in 24 studies. Forty-six percent were diagnosed with critical illness polyneuropathy and we were still puzzling about the underlying etiology, I would often hear the word ‘sepsis’ mentioned in the ICU. I asked intensivists, “What is this thing called sepsis?” At that time, while there had been extensive investigations, which continue to the present day, definitions and underlying mechanisms were uncertain.

Sepsis originally meant putrefaction, or decomposition of organic matter. Through culture techniques, Pasteur (1822-1895) (Figure 5) showed the decomposition was due to microorganisms, supporting the germ theory of infection.25 It was Robert Koch (1843-1910) (Figure 6) who first saw these germs under the microscope (Figure 7). Virchow, the father of cellular pathology, and a highly influential scientist was dismissive, “whole business seemed quite improbable”. Koch persisted and went on to great fame.28

In his famous textbook, The Principles and Practices of Medicine, published in 1892, Osler (1849-1919) wrote extensively on the effects of sepsis on the human body, including effects on the peripheral nervous system, where he observed “a rapid loss of flesh”29 (Figure 8). For many years this rapid loss of flesh was attributed to a catabolic myopathy, and respiratory muscle weakness to diaphragmatic fatigue. Before our observations were first published in 1983, several reports described patients who were remarkably similar to our own. Erbshloß in 1955 observed a polyneuropathy following anoxic coma after shock or cardiac arrest. In 1961, Mertens31 described “coma polyneuropathies” in patients who had circulatory shock associated with acute intoxication and severe metabolic crisis, seemingly due to metabolic and ischemic lesions of the peripheral nervous system. In 1971 Henderson et al32 described a polyneuropathy in patients with burns. Four septic patients developed a severe polyneuropathy in 1977, which Bischoff et al33 attributed to gentamycin sulfate.

There have been recent observations on the pathophysiology. Bostock and colleagues,35 Institute of Neurology, London, UK, utilized methods testing nerve excitability. They showed that motor axons in critically ill polyneuropathy patients are depolarized by two possible mechanisms: raised extracellular potassium or hypoperfusion. The last mechanism would fit with our theory of disturbances of the microcirculation to peripheral nerve.21 Allen et al36 King’s College Hospital, London, UK, utilized several electrophysiological techniques, and attributed a reduced muscle excitation threshold and conduction velocity to an acquired channelopathy. Again, I wonder if these changes could be explained by a disturbance of microcirculation to muscle.
Spin-offs

There have been several important spin-offs. I will mention two.

We had inferred that difficulty in weaning from the ventilator in critically ill patients was often due to the axonal degeneration of the peripheral nerves involved in respiration. At that time the techniques of phrenic nerve conduction and needle EMG of the diaphragm were rarely used. We therefore embarked on a series of investigations which developed the techniques and established them as valuable not only in the ICU but in other clinical settings. A wide variety of neuromuscular disorders were investigated. The book, Neurology of Breathing, by Bolton, Chen, Wijdicks, and Zifko, is an exposition of these investigations.37

In a broader perspective, Bryan Young and I recognized that in the Victoria Hospital 30-bed ICU, in addition to the primary neurological and neurosurgical admissions, such as head injury and stroke, there were the medical and surgical admissions, such as severe pneumonia or multiple trauma, that were often complicated by nervous system disease. Both groups required neurological and neurosurgical expertise. Hence, in 1991, we established the Canadian Neurocritical Care Group38, which has, often under the direction of Jeanne Teitelbaum, met and held successful yearly courses at the Canadian Neurological Sciences Federation. Over the years colleagues and I organized symposia dealing with various aspects of neurocritical care at national and international meetings. Recently the Canadian Neurocritical Care Group has evolved into the Canadian Neurocritical Care Society39, a collaborative effort of Canadian neurologists and neurosurgeons, and intensivists, the Canadian Critical Care Society. These arrangements were spearheaded by Draga Jiccic, neurologist, and David Zygun, intensivist. It is now possible for doctors to receive full training in Canada as neurointensivists.

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“I realize I couldn’t have done it without the players”. Casey Stengel, manager of the New York Yankees.

The “players” are too numerous to list here. Many will be found as co-authors in published abstracts, papers, and books. I must mention Bill Sibbald and Frank Rutledge, former Directors of our ICU, now deceased. Ms. Betsy Toth, University of Western Ontario, my former secretary, prepared almost all the manuscripts. Ms. Holly Shea, Queen’s University, prepared the present manuscript.

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