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A Hypothesis for the Cause of Complex Regional Pain Syndrome-Type I (Reflex Sympathetic Dystrophy): Pain Due to Deep-Tissue Microvascular Pathology

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Abstract

Complex regional pain syndrome-type I (CRPS-I; reflex sympathetic dystrophy) is a chronic pain condition that usually follows a deep-tissue injury such as fracture or sprain. The cause of the pain is unknown. We have developed an animal model (chronic post-ischemia pain) that creates CRPS-I-like symptomatology. The model is produced by occluding the blood flow to one hind paw for 3 hours under general anesthesia. Following reperfusion, the treated hind paw exhibits an initial phase of hyperemia and edema. This is followed by mechano-hyperalgesia, mechano-allodynia, and cold-allodynia that lasted for at least 1 month. Light microscopic analyses and electron microscopic analyses of the nerves at the site of the tourniquet show that the majority of these animals have no sign of injury to myelinated or unmyelinated axons. However, electron microscopy shows that the ischemia-reperfusion injury produces a microvascular injury, slow-flow/no-reflow, in the capillaries of the hind paw muscle and digital nerves. We propose that the slow-flow/no-reflow phenomenon initiates and maintains deep-tissue ischemia and inflammation, leading to the activation of muscle nociceptors, and the ectopic activation of sensory afferent axons due to endoneurial ischemia and inflammation.

These data, and a large body of clinical evidence, suggest that in at least a subset of CRPS-I patients, the fundamental cause of the abnormal pain sensations is ischemia and inflammation due to microvascular pathology in deep tissues, leading to a combination of inflammatory and neuropathic pain processes. Moreover, we suggest a unifying idea that relates the pathogenesis of CRPS-I to that of CRPS-II. Lastly, our hypothesis suggests that the role of the sympathetic nervous system in CRPS-I is a factor that is not fundamentally causative, but may have an important contributory role in early-stage disease.

Key Words. CRPS; RSD; Pain; Deep Tissue Microvascular Dysfunction

Symptomatology of Complex Regional Pain Syndrome-Type I

Complex regional pain syndrome-type I (CRPS-I) is a chronic pain syndrome that occurs following injuries such as sprains, fractures, and crush injuries that are not accompanied by a clinically verified nerve injury [1]. CRPS-I is a relatively rare disorder, with an estimated incidence of 26.2 per 100,000 [2]. Nevertheless, this condition has fascinated, perplexed, and frustrated clinicians for well over a century. Symptoms of CRPS-I include spontaneous pain ("burning" pain referred to the skin and "aching" pain referred to deep tissues) and a variety of stimulus-evoked abnormal pain sensations, including mechano-hyperalgesia, mechano-allodynia, cold-allodynia, and sometimes heat hyperalgesia. Other symptoms include disorders of vasomotor and sudomotor regulation; trophic changes in the skin, hair, nails, and bone; and dystonia and other motor abnormalities [3–9]. CRPS-II (causalgia) is similar in all respects except that a clinically verified nerve injury is present [3,4].

Until recently, it has been generally accepted that most, if not all, the ancillary symptoms of CRPS-I are due to a

hyperactive sympathetic outflow to the painful region, and that the sympathetic outflow is somehow causally related to the pain. This belief gained credence from the therapeutic benefit that is achieved in at least some patients following sympathectomy or local anesthetic block of the sympathetic ganglia [10]. However, it is well known that not all CRPS-I patients benefit from sympathetic interventions, and those that do sometimes receive only partial or temporary pain relief. Not surprisingly, the role of the sympathetic innervation in the CRPS-I syndrome is not well understood [11].

It is believed that there may be a temporal progression of symptoms in CRPS-I, resulting in three broadly defined stages of disease. The first is typified by hyperemia and edema, the second by cold, hyperhidrosis and cyanosis, and the third by dystonia and dystrophic changes [5,9]. There is some evidence that this temporal progression is not present in all patients [8]. Clinical experience and animal experiments suggest that the sympathetic innervation may contribute in the early stage of CRPS-I, but that the underlying pathology evolves from sympathetically maintained pain (SMP) to sympathetically-independent pain (SIP) [5,10,12,13].

A New Animal Model of CRPS-I

We have developed an animal model (chronic post-ischemia pain; CPIP) that creates CRPS-I-like symptomatology [14]. The CPIP model is produced in rats under general anesthesia with a tourniquet placed around the ankle for 3 hours. Following reperfusion, the hind paw exhibits an initial phase of hyperemia and edema lasting for 2–12 hours, followed by neuropathic pain (mechano-hyperalgesia, mechano-allodynia, and cold-allodynia) that lasts for at least 1 month. Light microscopic analyses and electron microscopic analyses of the hind paw nerves from CPIP rats show that nearly all have no sign of nerve injury due to the tourniquet [15]. Some of the animals have a small number of degenerating myelinated axons, which would be difficult or impossible to verify if present in a human patient. In addition, there are no changes in conduction velocity of the sural nerve at 5 and 7 days post-reperfusion [16]. However, there is a reduced density of the sensory fibers' terminal arbors in the epidermis in the injured hind paw, as determined by PGP9.5 immunohistochemistry [16], similar to that observed in CRPS-I patients [17].

Electron microscopic analysis of the hind paw digital muscle and digital nerves reveals microvascular pathology that is indicative of the capillary slow-flow/no-reflow phenomenon [15]—a well known consequence of ischemia-reperfusion (I-R) injury in cardiac and skeletal muscle. The hind paw muscle also exhibits poor perfusion and a reduced density of viable capillaries for a week following reperfusion [16]. Single fiber recordings from primary afferent axons in CPIP rats at intervals of 2–9 days after tourniquet release have found spontaneously discharging Aβ, Aδ, and C fibers in every case examined [15]. Normal sensory fibers have little or no spontaneous discharge.

Slow flow/no-reflow in deep-tissue microvasculature would be expected to produce a persistent inflammatory state. Data from the CPIP animals is consistent with this idea. Malondialdehyde, a product of free radical-induced lipid peroxidation, was significantly elevated in the CPIP rat hind paw, and CPIP allodynia was dose dependently attenuated by the antioxidant N-acetyl-L-cysteine, and the free radical scavenger 4-hydroxy-2,2,6,6-tetramethyl-piperydine-1-oxyl, suggesting a key role of free radicals [16]. Furthermore, the pro-inflammatory cytokines, tumor necrosis factor alpha (TNFα), interleukin-1 (IL-1) and interleukin-6 (IL-6), and the related transcription factor, nuclear factor kappa B (NFκB), are all elevated in the CPIP rat hind paws early after reperfusion, and both an IL-1 receptor antagonist and an NFκB inhibitor, pyrrolidine dithiocarbamate, dose dependently reduce CPIP allodynia, suggesting that an NFκB-dependent generation of pro-inflammatory cytokines plays a role in CPIP. Lactate is also increased in the muscle tissue of CPIP rat hind paws, and the levels of lactate are further elevated when the rats exercise. Exercise also decreases mechanical paw withdrawal thresholds in CPIP rats, and there is a direct correlation between mechanical allodynia and lactate levels in unexercised and exercised CPIP rats [16].

CPIP rats also develop a hypersensitivity to norepinephrine (NE), reflected by enhanced arterial responsiveness to NE, as well as enhanced painful responses to hind paw injections of NE [18]. Mice also develop CPIP after I-R injury, and CPIP mice have an upregulation of endothelin A (ET-A) receptors in their hind paw muscles. Accordingly, CPIP mice exhibit enhanced sustained nociceptive behaviors following hind paw injections of endothelin-1 (ET-1) [19].

A Hypothesis for the Pathogenesis CRPS-I

Our findings in CPIP animals lead us to propose a hypothesis that we believe to be applicable to both the CPIP animals and to at least a subset of CRPS-I patients. We propose that the fundamental cause of the pain is a persistent deep-tissue (muscle, bone, and nerve) ischemia and consequent inflammatory reaction produced by microvascular pathology subsequent to an I-R injury. We propose that the following processes (summarized in Figure 1) are critical to the initiation, development, and maintenance of the CPIP and CRPS-I syndromes.

CRPS-I is Initiated When an Inflammatory Response to a Deep-Tissue Injury Produces a Compartment-Like Syndrome that Impairs Blood Flow to Muscle, Nerve, and Bone

At its onset, CRPS-I is often characterized by significant regional edema that is sometimes described as "exaggerated" [20–22]. Edema develops due to the extravasation and accumulation of plasma in the interstitial space [23]. In the early stage of CRPS-I, there is plasma extravasation [20], increased density of perfused vessels, and higher capillary filtration capacity (an index of microvascular permeability) [24,25].

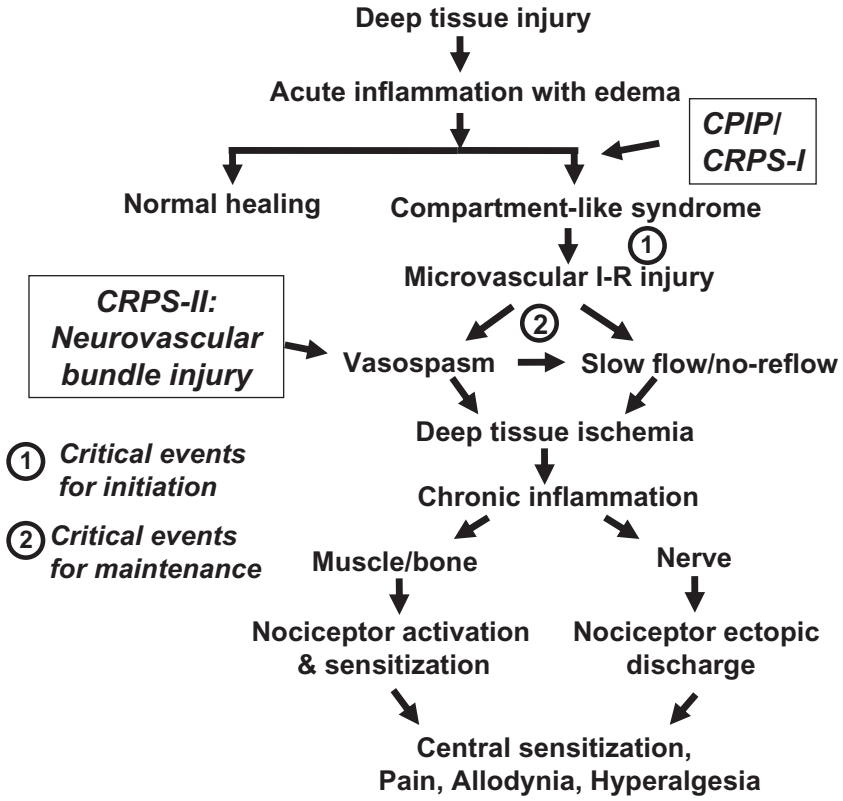

Figure 1 Schematic of the hypothesized pathophysiological mechanisms in the chronic post-ischemia pain (CPIP) model and at least a subset of complex regional pain syndrome-type I (CRPS-I) patients. In CRPS-I patients, deep tissue injury leads to edema and a compartment-like syndrome. Reperfusion (release of the tourniquet in the animal model) leads to injury of the microvascular endothelial cells induced by free radicals. These events lead to arterial vasospasms and slow flow/no-reflow in deep tissue microvasculature, which produces persistent ischemia that both spreads the ischemia-reperfusion (I-R) injury, and causes chronic inflammation. In muscle and bone, the resulting ischemia and inflammation (including generation of lactate) activates and sensitizes nociceptors. In nerve, the ischemia and inflammation cause ectopic nociceptor discharge. Injury to a neurovascular bundle may also evoke arterial vasospasm, and this may initiate the same vicious cycle in patients with CRPS-II (causalgia).

The pressure exerted by the interstitial accumulation of extravasated plasma within a relatively confined anatomical space occludes the capillaries of adjacent tissues and causes a compartment syndrome [26,27]. Pressures within a myofascial compartment of as little as 30–40 mm Hg will occlude all capillary flow [28,29]. Compartment syndrome is a well-known complication of fractures, joint trauma, and joint surgery [26,30–32]. CRPS-I also often follows fractures, joint injuries, and wrist, elbow, and knee surgery [33,34]. We think that it is extremely important to note that CRPS-I nearly always follows injury to deep tissues (fractures, sprains, surgeries, crush injuries, etc.). CRPS-I initiated by a strictly cutaneous injury (e.g., a laceration or burn) is exceedingly rare [35]. Edema in the subcutaneous space does not lead to a compartment syndrome.

In its most severe form, musculoskeletal compartment syndrome leads to ischemia that is severe enough to cause tissue necrosis, but subtotal or episodic (exertional) ischemia leads to compartment-like syndromes that do not progress to tissue necrosis [36–38]. We propose that in the CPIP animal, a compartment-like syndrome is created by the period of extensive edema that follows release of the tourniquet. In man, both compartment syndrome and CRPS-I are known risks of excessive tourniquet exposure [39,40].

The Compartment Syndrome Leads to an I-R Injury and Persistent Deep-Tissue Microvascular Pathology

While the proposed compartment-like syndrome does not produce tissue necrosis, it does produce microvascular

injury. Ischemic tissues accumulate oxidative enzymes, primarily xanthine oxidase and NADPH oxidase. Upon reperfusion, the accumulated oxidases reduce the returning molecular oxygen and the cells composing the microvessels are exposed to high levels of oxygen free radicals that damage both vascular endothelial and smooth muscle cells [41–48]. The onset of reperfusion is obviously well defined when a tourniquet is removed, but less clearly demarcated when the ischemia is due to a compartment-like syndrome. In the latter case, it is probable that reperfusion is episodic or partial, and may migrate from one part of the tissue's capillary bed to another.

I-R injury is a multifactorial phenomenon characterized by several pathological mechanisms affecting arterioles, capillaries, and venules [48–55]. These mechanisms interact and generally contribute to positive-feedback loops that perpetuate and worsen the I-R injury. Although most studied as a consequence of ischemic insult to heart muscle, I-R injury phenomena are also known to occur in the microvasculature of skeletal muscle [52,56]. We propose here that I-R injury also occurs in the microvasculature of bone and peripheral nerve.

I-R Injury, Arterioles, Vasospasm, and the Sympathetic Nervous System

Following I-R injury, the arteriole's endothelial cells release less nitric oxide and the reduced amount of nitric oxide that is released is converted to toxic nitrogen free radicals after interaction with oxygen free radicals. The result is a deficit in the nitric oxide-mediated vasodilatation that normally modulates the vasoconstriction that is evoked by the sympathetic nervous system [49,57,58]. Recent data show that CRPS-I patients have abnormal vasodilatation responses after sympathetically evoked vasoconstriction [59], and decreased levels of nitric oxide have been found in blister fluid from the affected region [60]. ET-1 is a potent vasoconstrictor derived from vascular endothelial cells that produces its pressor effects by acting on ET-A receptors on vascular smooth muscle cells [61]. Following I-R injury, ET-1 production and release are increased, and so is the vasoconstrictor response that it evokes [62]. Increased levels of ET-1 are found in blister fluid from the affected extremity in early-stage CRPS-I patients [60]. As we described above, CPIP mice have upregulated ET-A receptors in hind paw muscle, and show enhanced painful responses to intraplantar ET-1 injections [19].

I-R injury also evokes an upregulation of the expression of α-adrenoceptors on arterial smooth muscle cells, resulting in a threefold increase in the contractile response to NE [63]. As a result, arteries will spasm in response to normal levels of sympathetic discharge (vasoconstrictor "tone"), to the myriad of sympathetic reflexes that are evoked by daily activity, and perhaps to catecholamines (NE and epinephrine) that arrive via the circulation. As discussed above, CPIP rats exhibit enhanced arterial vasoconstrictor responses to NE. Both CRPS-I patients and CPIP rats display abnormal pain responses to intraplantar injections of NE [18,64]. There is clear evidence that there is dramatically reduced sympathetic reflex activity in early CRPS [65]. There is also evidence that this reduced sympathetic outflow itself results in a hypersensitivity of the smooth muscle adrenoceptors, that is, functional denervation supersensitivity [66]. There is evidence for increased vascular α-adrenoceptor responsiveness in CRPS-I patients [67–69]. The situation is likely to be very complex and variable from patient to patient, or from time to time in a given patient: increased vascular α-adrenoceptor responsiveness that might be driven by circulating catecholamines and/or the NE released in the context of decreased activity at the postganglionic sympathetic fiber's synapse. In any case, the result is that sympathetic activity would be contributory, rather than fundamentally causative, and exacerbate ischemia, inflammation, and consequent pain.

Nerve injury evokes sympathetic fiber sprouting in the dorsal root ganglion. However, there is evidence that this sprouting may not contribute to CRPS-II pain (and, by implication, CRPS-I pain) [70]. There is also evidence that nerve injury evokes the *de novo* expression of α-adrenoceptors on primary afferent nociceptors, which suggests a direct link between NE and epinephrine (via the circulation or via the sympathetic postganglionic synapse) and nociceptor activation [71]. The presence of such a mechanism is not incompatible with the hypothesis that we propose.

Vasospasm in precapillary arterioles exacerbates the ischemia and leads to further I-R injury, and may contribute to the spread of microvascular dysfunction. The resulting vicious cycle contributes to the maintenance and worsening of the ischemic state. Such spreading dysfunction may account for the "contiguous" spread of CRPS-I symptoms, that is, the tendency for edema and pain to gradually spread outward from the initially symptomatic region [72]. There is extensive evidence for such a spreading phenomenon in the case of ischemic heart disease [73]; we propose here that the same thing occurs in skeletal muscle. A long forgotten paper by Foisie [74] suggested that arterial vasospasm might contribute to causalgic-like pain after crush injuries and soft tissue injuries that did not injure a nerve (i.e., CRPS-I). Arterial vasospasm after I-R injury is sometimes relieved by a brief tourniquet application [75]. CRPS-I patients sometimes report temporary pain relief after brief tourniquet application [76,77].

I-R Injury to Capillaries

Free radicals also damage capillary endothelial cells and stimulate them to release various pro-inflammatory mediators. Free radicals increase the expression of selectins, intracellular and extracellular adhesion molecules [78], complement factors [79], leukotriene B_4 [80,81], and platelet activating factor [82,83]. Many of these molecules are chemotaxic and recruit monocytes, leukocytes, and platelets which accumulate and occlude the capillary

lumen, and release TNFα, IL-1, and IL-6, which produce toxic effects that might spread tissue injury to adjacent regions [84,85].

Occlusion of capillaries generates the phenomenon known as slow-flow/no-reflow, which we believe to be a key feature of both the CRPS-I and CPIP syndromes. Slow-flow/no-reflow is characterized by the swelling of microvascular endothelial cells, platelet aggregation, and plugging of the capillary lumen by leukocytes and erythrocytes [45,48,49,51,52,55,86–95]. "Slow-flow" refers to the condition where the lumen is partly occluded; complete occlusion is "no-reflow." In cardiac muscle, the onset of slow-flow/no-reflow is detectable immediately after reperfusion, but it worsens significantly during the following hours and days [55,96]. It is important to recall how easy it is to block capillary flow. The smallest capillaries are formed from a single endothelial cell, and their lumen diameters are nearly the same as the shortest diameter of a red blood cell. The lumens' diameter is restricted further at the level of the endothelial cell's nucleus. Red blood cells must deform and squeeze through the capillary lumen. The pain of a sickle cell crisis is due to ischemia that occurs because of an abnormality of the erythrocyte's membrane that makes it too stiff to deform and squeeze through the capillary lumen.

As well as occurring in skeletal muscle, we have evidence from the CPIP animals that slow-flow/no-reflow also occurs in the nerve's capillaries, and we think it likely that it also occurs in periosteal and intramedullary bone capillaries. There is no logical reason to suppose that slow-flow/no-reflow does not also occur in cutaneous capillaries. However, because of their important role in thermoregulation, the cutaneous capillary beds in the distal extremities of man are extremely dense and highly anastomotic; this renders the skin's capillary bed relatively resistant to slow-flow/no-reflow [97].

I-R Injury to Venules

Free radical damage to the endothelial cells of venules resembles that seen in capillaries. However, venules have lumens that have a greater diameter than that of capillaries and venules are thus relatively resistant to slow-flow/no-reflow. However, I-R injury causes damage at post-capillary venules, which causes leakage of plasma through resultant gaps between adjacent endothelial cells [98]. It is significant that plasma extravasation occurs mostly at the level of the venules, not the capillaries. Free radical damage to venules is thus the immediate cause of edema formation. As we discuss below, it is significant to note that a leaky venule has nothing to leak if its upstream capillary supply is blocked.

Compensatory Reactions to Microvascular Pathology

Although arterial vasospasm and slow flow/no-reflow would produce areas of tissue ischemia, the system responds with attempts to compensate via reactive hyperemia and arteriovenous shunting [52,56]. Limbs in early stages of CRPS-I often have high arterial flow, yet at the same time have elevated venous pressure and arteriovenous shunting [24,25]. These phenomena are likely to be due to slow-flow/no-reflow in the affected capillary bed. The alternation between ischemia and reperfusion provides a way to spare tissue from lethal injury, but it also creates a vicious cycle of I-R injury which maintains microvascular dysfunction.

Microvascular Pathology Leads to Persistent Ischemia which in turn Leads to Persistent Inflammation

We propose that microvascular pathology leads to an ischemic state that evokes persistent inflammatory responses.

Microvascular Pathology and Ischemia

Several observations are consistent with the presence of impaired blood flow in CRPS-I patients. Skin capillary hemoglobin oxygenation (HbO_2) is lowered and skin lactate is increased in CRPS-I limbs, suggesting that there is both impaired nutritive blood flow and enhanced anaerobic glycolysis [99,100]. Nail bed capillary flow is decreased [101], and reactive hyperemia in the cutaneous vasculature is impaired in CRPS-I patients [66]. Additionally, there is an impairment of high-energy phosphate metabolism in CRPS-I muscles [21,102], consistent with an impaired blood supply. Experimentally-evoked plasma extravasation is exaggerated in CRPS-I patients [103,104].

Several lines of evidence suggest that at least some CRPS-I patients have a persistent inflammatory condition. Necropsy studies of amputated limbs from patients with severe CRPS-I find lipofuscin deposits, atrophic fibers, and severely thickened capillary basal membranes in muscle and subcutaneous tissue [105,106], consistent with the presence of ischemia-evoked inflammation. Serum levels of calcitonin-gene related peptide and bradykinin are elevated in the venous drainage of CRPS-I limbs, consistent with the presence of an ongoing ischemic and inflammatory state in deep tissues [107,108].

Eisenberg et al. [109] have detected greatly elevated levels of inflammatory by-products (e.g., malondialdehyde) and cellular antioxidants in the serum and saliva of CRPS-I patients with typical disease. We suggest that these markers originate in tissues made ischemic and inflamed by slow-flow/no-reflow. There are several reports of increased levels of pro-inflammatory cytokines in CRPS-I patients [60,110–112], as would be expected if there was an ongoing inflammatory reaction. These findings are consistent with our results that malondialdehyde and pro-inflammatory cytokines are increased in the hind paw muscle of CPIP rats [16], as well as numerous reports that these mediators are elevated after skeletal I-R injury (see above).

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