

Why Pain Gets Worse: The Mechanism of Heat Hyperalgesia

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Pain differs from other senses in many ways; one of the most striking is that the intensity of pain increases with time in the presence of a painful stimulus, a process that is referred to as sensitization or hyperalgesia. With all the other senses, the perceived intensity decreases with continuous exposure to a constant stimulus. For instance, when you emerge from a cinema onto a sunny street you are at first dazzled, but soon adapt to the new and higher ambient light level. If vision behaved like pain the opposite would happen—the dazzling light of the street would become ever brighter. The reason for the difference is clear enough. Light adaptation allows us to operate over a wide range of ambient light intensities, a necessary property for any species that may at one moment be in bright sunlight and the next in a dark cave (possibly containing a bear). Pain, on the other hand, cannot be ignored as it often signals tissue damage, and it is essential for the integrity of the organism that a painful stimulus should become ever more pressing until the subject takes some action to remove its cause.

Thus hyperalgesia fulfills a valuable survival function, but it also has a major downside. When inflammation is chronic, for instance in an arthritic joint, hyperalgesia can be disabling because the only action the subject can take is to remain immobile, not a strategy with positive implications for survival in an animal, nor for emotional or economic well being in a human. Many of the early investigations in empirical pharmacognosy, otherwise known as folk medicine, were directed toward alleviating the pain resulting from inflammation. These investigations were conducted in a manner that we would now regard as highly unscientific, but they did score some notable successes. Amongst them were the discovery of two potent analgesics, in the shape of salicylic acid from willow bark, and opium from poppies. The descendants of both are, of course, still in widespread use today.

Modern science has taken a more rational strategy toward understanding hyperalgesia. We now recognize that it is not intrinsic to the pain-sensitive nerve terminals themselves, but instead depends on the release of extracellular proinflammatory mediators from stressed or damaged tissue. These mediators are many and di-

verse in origin, but amongst the best studied are bradykinin, ATP, prostaglandin E₂, and (surprisingly) nerve growth factor (NGF). NGF is of course a potent growth factor, which promotes the targeting of outgrowing nerve fibers in the developing organism, but it also seems to play a role in the adult organism, as a pro-inflammatory mediator amongst its other roles (Lewin et al., 1993).

The paper by Stein et al. (2006), on p. 509 of this issue, reports a highly interesting advance in our understanding of the molecular basis of hyperalgesia. The paper focuses on the mechanism by which the heat-activated ion channel, transient receptor potential vanilloid 1 (TRPV1), is sensitized by NGF. TRPV1 is one mechanism (although not the only one) by which we detect mild levels of painful heat, and its activation at around 43°C is likely to be responsible for the transition in the English language between the word “warm,” which has pleasant connotations and is used to describe heat below ~43°C, and “hot,” which signifies an unpleasant heat sensation above this threshold temperature. TRPV1 is strongly activated by increases in temperature >43°C, a property that sets it apart from most other ion channels, in which channel opening is only weakly temperature sensitive. The activation of heat-sensitive ion channels in sensory neurons was first characterized in work by Cesare and McNaughton (1996), and the relevant channel (at first named VR1) was subsequently cloned by the group of David Julius (Caterina et al., 1997). An important property of TRPV1 is that the temperature threshold is lowered by proinflammatory mediators such as bradykinin (Cesare and McNaughton, 1996), in a process called heat hyperalgesia. This property is the basis of the heat hyperalgesia caused by inflammation, because this aspect of hyperalgesia is abolished in mice from which TRPV1 has been deleted (Caterina et al., 2000; Davis et al., 2000).

As with any highly evolved function, heat hyperalgesia is a complex process to which several different mechanisms can contribute. Which mechanism is recruited depends on the identity both of the inflammatory mediator and of the intracellular signaling pathways

Abbreviations used in this paper: NGF, nerve growth factor; PIP₂, phosphatidylinositol 4,5-bisphosphate; TRPV1, transient receptor potential vanilloid 1.

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activated downstream of its binding to a receptor in the neuronal membrane. In roughly historical order, the proposed mechanisms are as follows:

(1) *Phosphorylation by PKC ϵ* . Bradykinin, ATP, and many other inflammatory mediators activate PKC, which in turn sensitizes the heat-activated current in neurons, which we now recognize as being carried by TRPV1 (Cesare and McNaughton, 1996). The main isoform involved is PKC ϵ (Cesare et al., 1999), and serines 502 and 800 are the critical sites for the sensitizing effect (Numazaki et al., 2002; Bhave et al., 2003) (NB residue numbers are from the rat TRPV1 sequence).

(2) *Removal of Inhibition by Phosphatidyl Inositol 4,5-Bisphosphate (PIP₂)*. An alternative pathway for the action of bradykinin, NGF, and other mediators that activate phospholipase C, leading to the metabolism of PIP₂, was proposed by Chuang et al. (2001). The idea here is that PIP₂ inhibits TRPV1 by binding directly to the ion channel, and that removal of PIP₂ by PLC would lead to sensitization. This idea was supported by experiments showing that application of either PLC or a PIP₂-sequestering antibody directly to TRPV1 expressed in membrane patches caused potentiation, and that deletion of a proposed PIP₂ binding domain in the C-terminal tail has a similar effect (Prescott and Julius, 2003).

(3) *Phosphorylation by PKA*. Prostaglandins and other inflammatory mediators activate PKA, which in turn phosphorylates TRPV1. The main effect seems to be via serine 116, and to involve a reduction in desensitization rather than a sensitization per se (Bhave et al., 2002).

(4) *Phosphorylation by Src*. Work in our group has recently identified a novel process by which NGF sensitizes TRPV1 by rapidly increasing the number of ion channels in the cell membrane (Zhang et al., 2005). The incorporation of new channels depends on activation of PI3 kinase, which in turn activates the nonreceptor tyrosine kinase Src. Phosphorylation by Src of a single critical residue in TRPV1, tyrosine 199, triggers the rapid movement of TRPV1 channels to the surface membrane.

(5) *Upregulation of Channel Expression*. NGF has the more long-term effect of upregulating de novo expression of TRPV1. The pathway involved is the Ras-MAPK pathway rather than the PI3K-Src pathway outlined above (Ji et al., 2002; Bron et al., 2003).

The role of mechanism 2, the relief of inhibition by PIP₂, is a particular focus of the paper by Stein et al. (2006). Doubt already had been cast on this model by work from Qin's group showing that stimulating the production of PIP₂ enhances rather than inhibits recovery of TRPV1 from desensitization (Liu et al., 2005),

and work from our lab, which showed that sensitization of TRPV1 by NGF can be explained by phosphorylation of TRPV1 by the tyrosine kinase Src, a mechanism completely independent of PIP₂ (Zhang et al., 2005). However, one rather obvious experiment that does not appear to have been done before is to apply PIP₂ directly to the cytoplasmic face of an isolated membrane patch. Stein et al. have performed this experiment, and the result is striking. Instead of inhibiting TRPV1, as predicted by the PIP₂ inhibition model, PIP₂ dramatically potentiates the activation of TRPV1 by capsaicin. The effect of PIP₂ itself is not completely reversible, presumably because the highly hydrophobic PIP₂ molecule remains in the membrane patch, but the potentiation produced by a version of PIP₂ with shorter carbon tails is readily reversible. In a second experiment, endogenous PIP₂ was removed by the highly cationic molecule polylysine. Instead of the potentiation expected in the original PIP₂ model, the capsaicin-activated current was inhibited, and the inhibition could be reversed by subsequent addition of PIP₂. The basic tenet of the PIP₂ model therefore does not seem to hold up; PIP₂ does not inhibit TRPV1, but instead potently enhances its activation. A similar enhancement of a number of other members of the TRP family of ion channels by PIP₂ has been described (for review see Hardie, 2006). Thus, in the end, TRPV1 seems to be similar to many other TRP channels, in that its activation is potentiated by PIP₂, rather than being an "outlier" that is inhibited by PIP₂.

Stein et al. next investigated the cellular signaling pathways by which activated TrkA potentiates TRPV1. Several largely independent signaling pathways radiate from activated TrkA. Three well-characterized downstream pathways involve PLC γ , PI3 kinase, and Ras-MAP kinase (Kaplan and Miller, 2000). In agreement with earlier studies (Bonnington and McNaughton, 2003; Zhuang et al., 2004; Zhang et al., 2005), Stein et al. found that the effect of NGF was abolished by wortmannin, an inhibitor of PI3 kinase. They make one new observation, though, which was not present in earlier accounts; they show that the p85 β subunit of PI3K interacts directly with TRPV1 via its SH2 domain. Yeast 2-hybrid experiments using the N terminus of TRPV1 as bait identify the p85 β subunit of PI3K as a binding partner; coimmunoprecipitation experiments show that TRPV1 and p85 β bind to one another; and experiments in which various domains of p85 β were isolated and tested for their ability to bind to TRPV1 in coimmunoprecipitation experiments show that only the SH2 domain bound TRPV1 to any significant extent. However, two aspects of the binding are unexpected: first, the binding was not found to be promoted by NGF, as might have been expected if PI3K is targeted to TRPV1 after activation of TrkA; and second, Stein et al. were unable to find any evidence that TRPV1 was phosphorylated on tyrosine residues. This last result is surprising because

the function of SH2 domains is to bind to phosphotyrosine residues, and the fact that the SH2 domain of p85 β binds to TRPV1 thus seems to imply that there must be some phosphotyrosine residues present in TRPV1. Zhang et al. (2005) have shown that tyrosines in TRPV1 are phosphorylated and that the phosphorylation is enhanced when TrkA is activated by NGF.

The final major area covered by Stein et al. relates to the mechanism by which NGF causes potentiation of TRPV1. Previous studies have identified a change in the activation properties of TRPV1 after phosphorylation by PKC: the temperature threshold for activation is lowered, and the dose–response relation for capsaicin shifts to lower capsaicin concentrations (mechanism 1 above; see Vellani et al., 2001). A second effect has been reported more recently: the number of TRPV1 channels in the membrane was found to be enhanced, after exposure to NGF, by a rapid translocation of TRPV1 channels from a cytoplasmic pool (Zhang et al., 2005). Stein et al. confirmed that the maximum current activated by a saturating concentration of capsaicin is increased by NGF. In addition they demonstrated that TRPV1 is rapidly translocated to the membrane by an elegant experiment in which the density of GFP-tagged channels in the membrane was directly visualized using total internal reflection (TIRF) microscopy.

What happens downstream of PI3K is still an open question. Work in our group shows that Src is activated, binds to TRPV1, and phosphorylates residue Y199 (Y200 in the human sequence); this phosphorylation could be a signal for translocation of TRPV1 to the membrane. Stein et al. suggest that the binding of PI3K to TRPV1 itself mediates translocation of TRPV1 to the surface membrane. Clearly there is a need for further experiments.

A satisfying degree of agreement is now beginning to emerge on most aspects of potentiation of TRPV1. Of the mechanisms outlined above, numbers 1 and 3–5 are still looking strong. In the case of mechanism 2, however, the emerging consensus is that the PIP₂ mechanism is not important in heat hyperalgesia, in direct contradiction to previous studies (Chuang et al., 2001; Prescott and Julius, 2003). The Stein et al. article raises the tantalizing possibility that PIP₂ may yet play a role, but as a potentiator of TRPV1 rather than as an inhibitor. The physiological role of this mechanism remains to be elucidated.

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