Perioperative myocardial infarction is a leading cause of morbidity and mortality after major non-cardiac surgery. Pharmacological agents such as beta-blockers may reduce the risk but are associated with side-effects and may be contra-indicated in some patients. Basic scientific experiments and preliminary clinical trials in humans suggest that remote ischaemic preconditioning (RIPC), where brief ischaemia in one tissue confers resistance to subsequent sustained ischaemic insults in another tissue, may provide a simple, cost-effective means of reducing the risk of perioperative myocardial ischaemia. The Medline and Pubmed databases were searched for articles concerning RIPC. The mechanism may be humoral, neural, or a combination of both, and involves adenosine, opioids, bradykinins, protein kinase C, and K-ATP channels, although the precise end-effector remains unclear. Small randomized trials in humans undergoing major surgery suggest that RIPC induced by brief lower limb ischaemia significantly reduces myocardial injury. It may also reduce other ischaemic complications of surgery and anaesthesia. Small studies provide some evidence that RIPC could reduce myocardial injury and other ischaemic complications of surgery. However, large-scale clinical trials to assess the effect of RIPC on mortality and morbidity are required before RIPC can be recommended for routine clinical use.
this technique could potentially reduce the incidence of PMI.\textsuperscript{2,7} Moreover, it has the potential to reduce the risk of other ischaemic complications of surgery such as acute tubular necrosis or stroke.\textsuperscript{41,51} We conducted a literature review of the background, putative mechanisms, and potential clinical utility of RIPC.

Methods
The Medline, Embase, and Pubmed databases were searched between 1986 and 2006 for relevant articles. The first description of ischaemic preconditioning (IPC) appeared in the literature in 1986.\textsuperscript{38} Combinations of the search terms ‘ischaemic’, ‘ischemic’, ‘preconditioning’, ‘tolerance’, ‘remote’, and ‘preconditioning at a distance’ were used. Additional papers were obtained from the reference lists of articles identified by the electronic database search.

Results
Ischaemic preconditioning
IPC describes the situation where tissues exposed to brief, non-lethal periods of ischaemia are rendered relatively resistant to damage from a subsequent prolonged ischaemic insult. The first published description\textsuperscript{38} found that the size of the myocardial infarction in canine hearts subjected to 40 min of coronary occlusion was significantly reduced if the heart was first exposed to four cumulative 5 min periods of ischaemia with reperfusion between each episode. This pivotal observation stimulated a flurry of experiments aimed at identifying the underlying mechanism, confirming cross-species preservation of IPC and assessing the potential clinical utility of IPC. The experiment proved to be reproducible in a number of different animal models,\textsuperscript{24,29,34} the effect was also observed in a range of non-cardiac tissues exposed to ischaemia,\textsuperscript{20,37,49}\textsuperscript{62} suggesting that an innate protective mechanism existed in mammalian tissue that could be exploited to protect against ischaemic injury.

The clinical utility of IPC has been investigated in clinical situations that involved direct interference with a tissue’s blood supply. In open heart surgery, it was shown that preconditioning led to relative preservation of myocardial adenosine triphosphate levels at the end of a subsequent 10 min ischaemic insult.\textsuperscript{60} A further study from the same group found that postoperative serum troponin T concentrations after coronary artery bypass grafting were significantly reduced if patients were exposed to several brief periods of reversed ischaemia before the fashioning of the first anastomosis.\textsuperscript{25} In a small study of 20 patients undergoing pulmonary surgery, there was a significant increase in superoxide dismutase and pulmonary vein oxygenation in the 10 patients who underwent preconditioning by temporary pulmonary artery occlusion, suggesting that the preconditioning reduces pulmonary ischaemia–reperfusion injury.\textsuperscript{5} Preconditioning produced a significant reduction in postoperative serum transaminase peaks after major hepatic resection.\textsuperscript{9} It also reduces haemodynamic instability during major hepatic surgery.\textsuperscript{8}

Although IPC reduces ischaemic injury, its clinical utility is limited to scenarios in which there is easy access to temporarily occlude the target organ’s blood supply, such as cardiology, cardiothoracic surgery, transplant, and plastic surgery. However, preconditioning one vascular bed also appears to protect organs in other vascular beds. This is RIPC or ‘preconditioning at a distance’.

Experimental evidence for RIPC
Analysis of canine models of cardiac IPC demonstrated that the size of infarctions in preconditioned hearts tended to increase in proportion to the area of the left ventricle at risk and, furthermore, that the distance between the edge of the infarct and the margin of the risk area increased as the risk region decreased. Conversely, this lateral distance remained the same in control hearts as the area at risk increased.\textsuperscript{48} These observations were formulated into a mathematical model, which suggested that a trigger generated in non-ischaemic tissue may contribute to the myocardial protection produced by conventional direct IPC.\textsuperscript{56}

The model implied that ischaemia induced in one coronary vascular bed may protect myocardium in another coronary vascular bed, a hypothesis subsequently confirmed in the canine heart. Dogs were randomized to undergo temporary occlusion of the circumflex coronary artery or not. They were then subjected to 1 h of ischaemia in the left anterior descending coronary bed. The extent of necrosis in the LAD bed was significantly reduced by preconditioning the circumflex bed.\textsuperscript{47} From a clinical perspective, this ‘intracardiac’ preconditioning was of limited utility, as it still requires direct interference with the coronary circulation.

The possibility of ‘inter-organ’ preconditioning was then explored. Gho and colleagues\textsuperscript{19} assessed the effect of transient coronary, mesenteric, or renal ischaemia on infarct size after 60 min of coronary occlusion. There was a significant reduction in infarction size with coronary and mesenteric preconditioning at normothermia, but not with renal preconditioning. Induction of hypothermia produced some enhancement of the coronary preconditioning effect, minimal improvement in the mesenteric preconditioning but unmasked a significant effect for renal preconditioning. Permanent mesenteric occlusion abolished the protection, implying that reperfusion was an essential element in obtaining the remote protection. These observations were subsequently confirmed in other studies.\textsuperscript{33,42,43,50,52,53,57,59}

The kidneys and, to a lesser extent, the intestine are vulnerable to damage from even brief periods of ischaemia. The blood supply of these organs is also inaccessible in many clinical scenarios, rendering them unsuitable as the remote stimulus for cardioprotection. Skeletal muscle, on the other hand, is relatively resistant to damage from ischaemia, and it
is easily accessible, and a direct preconditioning effect has been observed in animal models of skeletal muscle flaps.  

Skeletal muscle has been investigated as a remote stimulus for cardioprotection. Birnbaum and colleagues induced 30 min of skeletal muscle ischaemia in a rabbit model by means of a 55–65% reduction in femoral artery blood flow combined with electrical stimulation of the gastrocnemius muscle. When the animals were subsequently exposed to 30 min of coronary occlusion followed by 4 h of reperfusion, infarct sizes were considerably smaller in the animals that had received skeletal muscle preconditioning. Other investigators also found that transient limb ischaemia in rats protected against reperfusion tachyarrhythmias after 30 min of ischaemia while it also reduced infarction size in pigs exposed to 40 min of coronary occlusion. These animal models implied that RIPC of the heart could be achieved clinically by transient limb ischaemia.

**Mechanisms of RIPC**

The precise mechanisms involved in direct preconditioning are not yet established, although the K-ATP channels appear to have a fundamental role. Bradykinin, opioids, and adenosine act on cell surface receptors. Delta-opioid and bradykinin B2 bind to protein kinase C (PKC) and a tyrosine kinase via interactions with PI3-kinase, oxygen radicals, and mitochondrial K-ATP channels. Adenosine acts via a more direct pathway, coupling with PKC via A1/A3 receptors. The kinases are thought to then act on the end-effector, which may be mitochondrial K-ATP, to prevent opening of a mitochondrial transition pore.

Less is known about the mechanisms underlying RIPC. In general, signalling from one tissue to another may be achieved by humoral or neural pathways. Dickson and colleagues found that reperfusion was an essential requirement for obtaining a preconditioning effect, implying that ischaemic tissue releases some mediator which triggers preconditioning in distant tissues if it enters the general circulation, that is, a humoral pathway. Dickson and colleagues demonstrated that the preconditioning effect can be transferred between isolated hearts in a modified Langendorff apparatus. One group of isolated rabbit hearts were preconditioned. Fluid washed through the coronary vasculature was then collected and infused into separate isolated receptor hearts. Receptor hearts which received effluent from preconditioned donor hearts demonstrated reduced infarction size when subsequently subjected to prolonged ischaemia compared with hearts which received effluent from control, non-preconditioned donor hearts.

Adenosine, bradykinin, and opioid release from ischaemic tissues do appear to be involved in the RIPC pathway, just as they play a role in direct preconditioning. The administration of a PKC blocker abolishes the cardioprotective effect of transient infra-renal aortic occlusion or mesenteric occlusion and the direct preconditioning effect of transient coronary occlusion, suggesting that PKC activation is an event common to both direct and remote pathways. Moreover, PKC activation is higher in remote preconditioned hearts compared with controls. This PKC activation in RIPC may be triggered by adenosine, bradykinin, or opioids. An adenosine-receptor antagonist abolishes the cardio-protective effect of both direct cardiac preconditioning and remote renal preconditioning. A bradykinin-receptor antagonist blocks the cardioprotective effect of mesenteric preconditioning, by inhibiting activation of PKC, whereas infusion of bradykinin into the mesenteric circulation mimics the cardioprotective effect. A1-opioid receptor inhibition abolishes both direct and remote cardiac preconditioning. However, although inhibition of endogenous free radicals has little effect on infarct size in directly preconditioned myocardium, it reduces the protection provided by RIPC.

There is also evidence of a potential neural pathway in RIPC. The cardioprotective effects of RIPC in a rat model are significantly reduced by capsaicin-denervation or truncal vagotomy. Ganglion blockade with hexamethonium prevents PKC activation in rats, impeding the RIPC effect when the stimulus is brief mesenteric occlusion, although not when the stimulus is infra-aortic occlusion.

In a pig model of heart transplantation, RIPC with transient limb ischaemia in the recipient animals reduced the extent of myocardial infarctions in subsequently transplanted hearts. The effect was abolished by administration of glibenclamide, a K-ATP channel blocker. Given that transplanted hearts have no innervation, these data appear to suggest that RIPC cannot be produced by a neural mechanism. On the other hand, a recent study in humans found that administration of a ganglion blocker attenuated the effect of RIPC on endothelial ischaemia–reperfusion injury assessed by flow-mediated vasodilatation.

There may be some overlap between potential humoral mediators and neural pathways. Experiments in a rabbit model of RIPC using renal ischaemia as the stimulus demonstrated that adenosine released by the ischaemic kidney acted locally on the afferent renal nerves to trigger myocardial protection. A series of experiments using a rat model demonstrated that adenosine released locally during small intestinal ischaemia stimulates afferent nerves in the mesenteric bed during early reperfusion, triggering a neural pathway that activates myocardial adenosine receptors.

**RIPC in humans**

Although the mechanism of RIPC has yet to be clarified, several groups have produced preliminary results of trials of RIPC as a cardioprotective technique in humans. A study of eight male patients undergoing coronary artery bypass surgery, four of whom received brief periods of upper limb ischaemia after bypass, was inconclusive, probably due to an inadequate sample size. Brief upper limb ischaemia reduced endothelial dysfunction in human volunteers subjected to subsequent prolonged ischaemia in the contralateral arm.
These small proof of concept trials have been followed by two studies designed to assess the effect of transient lower limb ischaemia on myocardial injury after major surgery. Cheung and colleagues\(^7\) studied children undergoing open heart surgery and randomized them to receive four 5-min cycles of lower limb ischaemia as a RIPC stimulus. The method of randomization was not stated. Ischaemia was induced by inflating a blood pressure cuff to a pressure of 15 mm Hg greater than the systolic arterial pressure obtained via an arterial line. RIPC was performed about 5–10 min before the initiation of cardiopulmonary bypass. The patients underwent a range of cardiac procedures, including ventricular and atrial septal defect repair, valve repair, surgery for tetralogy of Fallot, and transposition of the great arteries. There were no significant differences in the distribution of surgical procedures between the RIPC and control arms, although the sample was small. However, the control patients tended to be older and larger. Again, this probably reflects the small sample size and it seems likely that the two groups were not entirely similar in terms of age, weight, or surgical procedure performed. However, the cross-clamp and bypass times were comparable. Of 37 patients recruited, 17 were assigned to the RIPC arm. The RIPC patients had significantly less myocardial damage (lower serum troponin I concentrations), but both groups exhibited a similar pattern of troponin elevations, with an immediate rise in the first few hours, tailing off by 24 h. Thus, RIPC reduced but did not eliminate myocardial injury. RIPC also produced a statistically significant reduction in inotrope requirements, although the actual reduction was only on the order of 2–3 \(\mu\)g kg\(^{-1}\)min\(^{-1}\).\(^7\) Despite the apparent reduction in myocardial damage and inotrope requirements, the length of the postoperative critical care stay was unchanged, the RIPC group requiring a mean stay of 54.2 (40.7) h compared with 39.5 (25.7) h for the control group. In this small study, RIPC did not appear to produce a tangible clinical benefit.\(^7\)

In major vascular surgery,\(^2\) we studied 82 patients undergoing elective open abdominal aortic aneurysm repair who were randomized to receive RIPC or not. The RIPC protocol used clamping to each common iliac artery (lower serum troponin I concentrations), but both groups exhibited a similar pattern of troponin elevations, with an immediate rise in the first few hours, tailing off by 24 h. Thus, RIPC reduced but did not eliminate myocardial injury. RIPC also produced a statistically significant reduction in inotrope requirements, although the actual reduction was only on the order of 2–3 \(\mu\)g kg\(^{-1}\)min\(^{-1}\).\(^7\) Despite the apparent reduction in myocardial damage and inotrope requirements, the length of the postoperative critical care stay was unchanged, the RIPC group requiring a mean stay of 54.2 (40.7) h compared with 39.5 (25.7) h for the control group. In this small study, RIPC did not appear to produce a tangible clinical benefit.\(^7\)

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Other potential applications of RIPC

At present, most work has focused on RIPC as a cardio-protective technique. However, it could protect other organs from ischaemia–reperfusion injury. Cheung and colleagues\(^7\) reported reduced airway resistance in patients exposed to RIPC, providing human data to support the observation that RIPC reduces lung ischaemia–reperfusion injury in animals.\(^58\) Other animal studies suggest that RIPC may protect against renal ischaemic injury.\(^21\) It also protects distant muscle beds from ischaemic injury\(^1\) and has a protective effect on the central nervous system.\(^23\)

Initial clinical trials of RIPC as a reno-protective and neuro-protective technique in major vascular surgery are underway in our unit.

Further studies

Although there is conflicting evidence of clear clinical benefit from RIPC,\(^2\)\(^7\) the technique could have the potential to reduce perioperative myocardial injury. The optimum pre-conditioning protocol (clamping of the iliacs or tourniquet-induced ischaemia) is unclear, as both have demonstrated some benefit. On a practical level, however, tourniquet-induced ischaemia is easier. Data on effect of RIPC on hard clinical end-points such as perioperative death, cardiac arrest, and hospital stay are lacking. Large clinical trials are required to determine whether there is a true clinical benefit to RIPC or whether it merely reduces biochemical markers without affecting prognosis. Some form of risk stratification should be incorporated into the design of any such trial in order to ensure an even distribution of risk between the arms of the study. In addition, anaesthetic techniques should be standardized, as volatile anaesthetics have a preconditioning effect.\(^18\)\(^44\)\(^63\)

Conclusion

The mechanisms of RIPC are complex and poorly understood. However, initial results from clinical trials suggest that this technique could potentially reduce perioperative myocardial injury. It raises the possibility of ameliorating the consequences of ischaemic injury in other tissues.

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Cardioprotection by remote ischaemic preconditioning

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