Much of the mortality following myocardial infarction results from remodeling of the heart after the acute ischemic event. Cardiomyocyte apoptosis has been thought to play a key role in this remodeling process. In this issue of the JCI, Diwan and colleagues present evidence that Bnip3, a proapoptotic Bcl2 family protein, mediates cardiac enlargement, reshaping, and dysfunction in mice without influencing infarct size (see the related article beginning on page 2825).

Postinfarct remodeling: the road to heart failure
Thrombotic occlusion of an epicardial coronary artery triggers acute myocardial infarction. This cataclysmic event, which takes place approximately 1 million times per year in the US, sets into motion a spatially and temporally complex set of processes. In the region supplied by the occluded coronary artery (Figure 1), cardiomyocytes undergo massive cell death by apoptosis and necrosis (1). The sudden loss of a significant portion of myocardium leads to decreases in contractile function. These changes are compensated by increases in left-ventricular volume, which augment contractility in the noninfarcted myocardium via the Frank-Starling mechanism. A negative consequence of enhanced left-ventricular volume, however, is intensified wall stress. This is partially counteracted by scar formation in the infarct zone and cardiomyocyte hypertrophy in the noninfarcted myocardium. These mechanisms provide temporary compensation for the loss of myocardium. While most patients recover from acute myocardial infarction, those with larger infarcts often progress to chronic heart failure due to cardiac remodeling (2). This process involves both expansion of the infarct and changes in the geometry of the noninfarcted myocardium. The result is an enlarged, more spherical, and thin-walled left ventricle with poor contractile function. Drugs that attenuate postinfarct remodeling improve cardiac function and reduce mortality (2). The mechanisms underlying cardiac remodeling are incompletely understood, but inflammation (3), extracellular matrix remodeling (3), and cardiomyocyte hypertrophy (4) and apoptosis (5) have been implicated.

Apoptosis: a mechanistic component of myocardial infarction
Apoptosis accounts for a significant portion of the large burst of cell death during acute myocardial infarction. Whole animal studies in which myocardial infarction was induced by ischemia/reperfusion (occlusion of a coronary artery followed by resumption of blood flow) have shown that genetic or pharmacologic inhibition of cardiomyocyte apoptosis decreases infarct size with concomitant preservation of cardiac function (6, 7). These studies indicate a causal role for cardiomyocyte apoptosis in the pathogenesis of infarction. In contrast to the infarct, lower levels of cardiomyocyte apoptosis are present in the noninfarcted myocardium in the weeks to months following infarction (5) and may play a role in remodeling and progression to heart failure (8).

Apoptosis is mediated by two pathways, one involving cell surface receptors and the other the mitochondria and endoplasmic reticulum (9). During apoptosis, the mitochondria are stimulated to release apoptogens, including cytochrome c, that activate downstream caspases and bring about the demise of the cell. The transmission of death signals to the mitochondria involves Bcl2 homology domain 3–only (BH3-only) proteins, a proapoptotic subclass of the Bcl2 family (10). BH3-only proteins are activated through transcriptional and posttranslational mechanisms and translocate to the outer mitochondrial membrane. Interactions between BH3-only proteins and multidomain Bcl2 proteins trigger the release of apoptogens, thereby causing apoptosis (11, 12).

Bcl2 and nineteen-kilodalton interacting protein–3 (Bnip3) is an atypical BH3-only protein because its BH3 domain possesses limited homology and, in contrast to typical BH3-only proteins, this domain is not required for cell death (13, 14). Bnip3 is present at low levels in several tissues, but its expression is markedly induced by hypoxia in a hypoxia-inducible factor–1α–dependent manner (15). In healthy cells, Bnip3 is loosely associated with mitochondria (16). In response to certain apoptotic signals, however, it inserts via a transmembrane domain into the outer mitochondrial membrane and triggers cell death. Whether this cell death occurs through apoptotic or nonapoptotic means remains controversial (17–21).

Inactivation of Bnip3 decreases cardiac remodeling following infarction
In this issue of the JCI, Diwan et al. inactivated Bnip3 in the mouse and gained insights into the role of apoptosis in cardiac remodeling (22). Loss of other BH3-only proteins has been shown to limit infarct size (23). Surprisingly, Diwan et al. found no difference in infarct size in wild-type and Bnip3-null mice subjected to ischemia/reperfusion. In contrast, Bnip3 ablation decreased apoptosis in the noninfarcted myocardium in the days following infarction. Moreover, the remodeling that takes place in the weeks following infarction was markedly attenuated in Bnip3-knockout mice as compared with wild-type mice. Increases in left-ventricular end-diastolic volume and sphericity were greater in wild-type mice than Bnip3-knockout mice. While systolic function decreased acutely in both groups following infarction, it continued to deteriorate in wild-type mice while stabilizing in Bnip3-knockout mice. These data indicate that Bnip3 mediates both cardiomyocyte death in the noninfarcted myocardium and cardiac remodeling.

Bnip3 in the infarct zone: too little, too late?
How is it that Bnip3 is involved in cell death in the noninfarcted myocardium but not in the infarct itself? The authors posit that this may be attributable to differences in Bnip3 levels in these two zones. Bnip3 is expressed at low basal levels and induced by hypoxia in a variety of cell types, including cardio-

Nonstandard abbreviations used: BH3, Bcl2 homology domain 3; Bnip3, Bcl2 and nineteen-kilodalton interacting protein–3.

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myocytes (15, 24). While Bnip3 is sufficient to kill cardiomyocytes (18), there appears to be inadequate time for $Bnip3$ expression to increase in a developing infarction. On the other hand, one would predict robust induction of $Bnip3$ expression in the noninfarcted and severely hypoxic myocardium. To address these issues, it will be necessary to assess the temporal and spatial localization of hypoxia, $Bnip3$, and cell death in the postinfarct heart.

**Which cell types mediate cardiac remodeling?**

Diwan et al. (22) attributed improvement in postinfarct remodeling to inhibition of cardiomyocyte apoptosis in the noninfarcted myocardium. Postinfarct remodeling involves a complex interplay among multiple hematopoietic and resident cardiac cell types (3). The use of a generalized $Bnip3$ knockout in this study raises the question as to which cell type(s) mediate remodeling. Although Diwan et al. showed that the number and distribution of hematopoietic cells under basal conditions were unaffected by $Bnip3$ inactivation, these cells were not analyzed following recruitment into the milieu of the infarcting heart. As one example, macrophages in an infarct stimulate fibroblast proliferation and matrix remodeling and, after exerting their effects, undergo apoptosis (3). Since $Bnip3$ expression is induced by hypoxia in macrophages (25), it is possible that apoptosis of these cells in the healing infarct zone is impaired in $Bnip3$-knockout mice. Abnormal macrophage persistence could account for a thicker scar in the infarcts of $Bnip3$-knockout mice, as observed by Diwan et al., and resultant reductions in wall stress and ventricular dilatation. If this hypothesis is correct, this sequence of events represents an additional mechanism—one that originates within the infarct zone rather than the noninfarcted myocardium—by which $Bnip3$ absence would ameliorate postinfarct remodeling. These effects of $Bnip3$ in the infarct zone may complement those described by Diwan et al. in the noninfarcted myocardium.

**Putting the brakes on cardiac remodeling**

Limitation of infarct size and inhibition of remodeling are currently the cornerstones of therapy for myocardial infarction (2). Coronary reperfusion reduces infarct size, resulting in preservation of functional myocardium and thereby limiting the primary stimulus for remodeling. Postinfarct remodeling is inhibited using pharmacological (e.g., angiotensin I–converting enzyme [ACE] inhibitors) or mechanical unloading therapies in patients with significant systolic dysfunction. Despite optimal therapy, however, substantial numbers of patients progress to chronic heart failure following myocardial infarction. For this reason, there is a need for additional pharmacological strategies directed specifically against critical mediators of remodeling.

$Bnip3$ appears to be one such critical mediator of remodeling and possesses
some attractive biological characteristics as a drug target. First, its site of action within the central death machinery may provide a target for specific inhibition of cell death. Second, its low basal levels in most tissues may minimize the possibility of untoward effects in nontarget organs. Third, the fact that Bnip3 is induced in response to hypoxia suggests that there is a temporal window, prior to significant Bnip3 accumulation and cell death, during which treatment could be beneficially instituted. Despite these characteristics, significant logistical hurdles exist in designing a practical pharmacological approach to inhibit this intracellular protein.

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Address correspondence to: Richard N. Kitsis, Albert Einstein College of Medicine, 1300 Morris Park Avenue, Bronx, New York 10461, USA. Phone: (718) 430-2609; Fax: (718) 430-8989; E-mail: kitsis@aecom.yu.edu.

In this issue of the JCI, Morioka et al. report on mice with a whole-pancreas knockout of the leptin receptor that exhibit improved glucose tolerance due to enhanced insulin secretion (see the related article beginning on page 2860). At first glance, their findings are very different from those reported in another recent study in which β cell–specific and hypothalamic knockout of the same gene caused obesity and impaired β cell function. The differences, which are understandable when one considers the body weights of the animals studied, provide new insight into the links among insulin, leptin action, and β cell function.

The prevalence of both obesity and type 2 diabetes are increasing at an alarming rate. Clearly, an improved understanding of the mechanisms involved in energy homeostasis will be required to halt these epidemics. In 1994, the cloning of the peptide hormone leptin, an adipocyte-derived factor secreted in proportion to body fat, opened new doors for exploring the molecular mechanisms underpinning energy homeostasis (1). However, despite an avalanche of new knowledge gained since then, many fundamental questions remain unanswered, including how systems regulating energy homeostasis interface with those that regulate glucose homeostasis.

Leptin and glucose homeostasis

Mice and humans that are deficient in either leptin (in the case of ob/ob mice) or the leptin receptor (db/db mice) not only develop obesity, but become both insulin resistant and glucose intolerant and are at high risk to develop diabetes (1–3). The pro-