Molecular Mechanisms of Cardiovascular Toxicity of Targeted Cancer Therapeutics

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Abstract: In 2002, Hoshijima and Chien drew largely theoretical parallels between the dysregulation of the signaling pathways driving cancer and those driving cardiac hypertrophy (Hoshijima M, Chien KR. J Clin Invest. 2002;109:849–855). On the surface, this statement appeared to stretch the limits of reason, given the fact that cancer cells are known for their proliferative capacity, and adult cardiomyocytes are, except under unusual circumstances, terminally differentiated and incapable of re-entering the cell cycle. However, on closer examination, there are numerous parallels between signaling pathways that drive tumorigenesis and signaling pathways that regulate hypertrophic responses and survival in cardiomyocytes. Indeed, this issue appears to be at the core of the cardiotoxicity (often manifest as a dilated cardiomyopathy) that can result from treatment with agents typically referred to as “targeted therapeutics,” which target specific protein kinases that are dysregulated in cancer. Herein, we examine the cardiotoxicity of targeted therapeutics, focusing on the underlying molecular mechanisms, thereby allowing an understanding of the problem but also allowing the identification of novel, and sometimes surprising, roles played by protein kinases in the heart. (Circ Res. 2010;106:21-34.)

Key Words: cardiotoxicity ▪ cancer ▪ therapeutics ▪ kinase inhibitors

Cancer therapeutics have evolved dramatically over the past few years. This has revolutionized the approach to treatment of some cancers. These novel treatment strategies target specific factors that are causal (or strongly contributory) in the initiation and progression of disease. The greatest advances have come with the development of monoclonal antibodies and small molecule inhibitors of protein kinases, typically receptor tyrosine kinases. Herein, we focus on the small molecules. At present, 11 agents are FDA-approved, with several more seeking approval over the next 2 years (Table 1). Although these agents offer new hope to many cancer patients, with some agents, treatment has been associated with cardiovascular complications including significant hypertension, left ventricular dysfunction, and/or heart failure. This is not a so-called “class effect,” however, because risk of significant cardiotoxicity for most of the approved agents appears to be low. However, the caveat to this statement is that, because of the recent introduction of these drugs, long-term follow-up of patients is not available. Long-term follow-up is particularly important with kinase inhibitors because as opposed to traditional chemotherapeutics, kinase inhibitors are often taken for life because if they...
Role of Protein Kinases in Cancer: Cellular Transformation, Tumor Growth, and Tumor Angiogenesis

Data from tumor sequencing projects have found remarkable mutation rates in protein kinases. One study found that mutations in as many as 120 kinases (or ≈20% of the kinome) could be present in individual cancers. Furthermore, there was evidence that these mutations were not just bystanders but were so-called driver mutations (ie, playing a role in tumorigenesis). Given this complexity, it seems inconceivable that inhibiting individual kinases in cancer would be effective, except for the relatively rare malignancies that are truly “oncogene-addicted” to a specific kinase. Surprisingly, “targeted therapeutics,” a term that refers to drugs that inhibit the specific gene products that drive tumorigenesis, have radically transformed the treatment of some hematologic malignancies and solid tumors.

Although the gain of function mutations, gene amplifications, and/or overexpression that drive tumorigenesis can occur in a variety of different gene classes, in many cases (but not all; see below), the genes encode protein kinases, typically tyrosine kinases. Approximately 90 of the 518 kinases in the human kinome are tyrosine kinases (TKs), and can be either receptor (RTKs, of which there are 58) or nonreceptor TKs of which there are 32 that can be divided into 9 subfamilies (eg, Src family). The identification of these mutated or amplified oncogenes has allowed the development of therapeutics specifically targeting the oncogenic kinases. Although oncogenic mutations commonly occur in other classes of proteins in addition to kinases (eg, cell cycle regulators, and pro- or antiapoptotic factors), kinases have become favorite targets of the pharmaceutical industry due not only to their importance in tumor initiation and progression but also to the relative ease with which inhibitors can be made (see below). This has led to an explosion in drug development targeting TKs (TK inhibitors [TKIs]) and, to a lesser but increasing extent, serine/threonine kinases.

The first TKI to reach market was imatinib (Gleevec, Novartis), and it was approved in 2001. It is still the most successful TKI with $3.67 billion in sales in 2008. Imatinib revolutionized the treatment of chronic myeloid leukemia (CML). Before the introduction of imatinib, CML was uniformly fatal within 5 years, whereas now, ≈90% of patients are alive 5 years after diagnosis. Indeed, this and other drugs have changed our thinking about cancer, which can now be viewed as a group of diseases that, even if not curable, can be managed effectively for years, similar to many other chronic diseases.

Imatinib was designed to target Bcr-Abl, which is causal in >90% of cases of CML and ≈20% of acute lymphocytic leukemia (ALL). The Bcr-Abl fusion protein is created by a

Ultimately, clinicians will need to develop approaches to patients that balance effective treatment of the cancer with risk of cardiotoxicity. For example, in a patient with metastatic disease, risk of cardiotoxicity becomes a very minor concern. However in a patient being offered adjuvant therapy who already has a good prognosis, risk of cardiotoxicity becomes more important.
balanced translocation in bone marrow progenitor cells that creates the Philadelphia chromosome. The protein contains part of the nonkinase domain of Bcr (a kinase of unclear function) and the kinase domain of the nonreceptor TK c-Abl. The Bcr-Abl fusion dimerizes leading to cross-phosphorylation and constitutive activation of the Abl kinase domain. This suppresses apoptosis by activating the Ras-Raf-ERK pathway (which increases antiapoptotic Bcl2 expression), the phosphatidylinositol 3-kinase (PI3K)-Akt pathway (which inhibits the proapoptotic factors Bad and FOXO3A), and STAT5 (signal transducer and activator of transcription 5) (which induces expression of antiapoptotic Bcl-x). Imatinib blocks all Bcr-Abl-dependent signaling leading to apoptosis in CML cells: one example of oncogene addiction.

Escape from imatinib suppression of CML occurs and often leads to blast crisis. In most cases, this is attributable to spontaneous point mutations within the ATP-binding pocket of Bcr-Abl. These mutations, which arise from the inherent genomic instability of malignant cells, typically reduce binding affinity of imatinib to the ATP pocket. The power of targeted therapeutics is that knowing this, more potent agents (eg, nilotinib and dasatinib; Table 1), which inhibit Bcr-Abl and all Bcr-Abl drug resistant mutants except the missense mutation that creates Bcr-Abl (T315I). Indeed, “intelligently” designed inhibitors can be created based on the known structure of the pocket harboring the mutation.

Although not originally designed to do so, imatinib was later found to inhibit 2 additional protein kinases that are involved in a variety of malignancies: (1) c-Kit, the receptor for stem cell factor, which is overexpressed in gastrointestinal stromal tumors (GISTs) (a rare tumor of the upper gastrointestinal tract derived from cells of neuroendocrine origin) and is mutated in systemic mastocytosis; and (2) platelet-derived growth factor receptors (PDGFRs) (Table 1). Fusion proteins involving PDGFRs such as FIP1L1-PDGFRα and ETV6-PDGFRα cause rare diseases including hypereosinophilic syndromes, dermatofibrosarcoma protuberans, and chronic myelomonocytic leukemia. Mutations and overexpression of PDGFRs play key roles in other cancers including GIST and glioblastoma.
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Inhibits at least 50 kinases. This can (and does) lead to off-target toxicity, which may include cardiotoxicity.

The so-called "off-target" effects (ie, a kinase not intended to be inhibited by a drug) leads to toxicity. If one of these kinases plays a critical role in the heart, the off-target toxicity may include cardiotoxicity.

Mechanisms of Action of the TKIs
Small molecule kinase inhibitors typically compete with ATP for binding to the ATP pocket. If ATP cannot bind, phosphotransferase activity is blocked and downstream substrates cannot be phosphorylated, even if the kinase is fully activated. In the cell, ATP is present in mM concentrations but TKIs will be present in nanomolar to very low micromolar concentrations. Thus the compounds must bind with very high affinity. Because the structure of the ATP pocket is conserved across the more than 500 kinases of the human genome, it is relatively easy to make an inhibitor that blocks a kinase of interest. However, it is not surprising that lack of selectivity is an issue with most kinase inhibitors that target the ATP pocket (termed Type I inhibitors). For example, based on an assay that determines the avidity with which a drug binds to a panel of kinases, it is predicted that sunitinib inhibits at least 50 kinases. This can (and does) lead to so-called "off-target" effects (ie, a kinase not intended to be inhibited by a drug is inhibited and this leads to toxicity). If one of these kinases plays a critical role in the heart, the off-target toxicity may include cardiotoxicity.

On-Target Toxicity
What are the underlying molecular mechanisms of this toxicity? As noted above, there are 2 types of toxicity. The first is off-target toxicity (also known as mechanism-based or target related). An ideal target in cancer would be one that serves a discrete yet critical function in the cancer cell but is dispensable for the function of all other cells. Unfortunately
this appears to be a very small minority of targets. More commonly, targets mediating cancer progression play key roles in other organ systems including the heart and vasculature (Table 2), and inhibiting these kinases leads to on-target toxicity. This is a fairly straightforward problem to understand but is obviously difficult to address clinically.

To illustrate on-target toxicity, we use the example of imatinib. To identify mechanisms of imatinib cardiotoxicity, Kerkela et al used neonatal rat cardiomyocytes in culture to demonstrate that incubation of cells with imatinib, in the absence of any other stressor, led to activation of the endoplasmic reticulum (ER) stress response.19 This included sustained activation of the IRE1 kinase arm of the response, culminating in activation of the ASK1/JNK pathway and cell death (Figure 1). To identify the specific target of imatinib, inhibition of which mediated cardiomyocyte death, there were several possibilities (Figure 2): c-Abl and the highly related ARG (Abl-related gene or Abl2), PDGFRs, c-Kit, the

<p>| Table 2. Kinase Targets in Cancer and Their Roles in the Cardiovascular System |</p>
<table>
<thead>
<tr>
<th>Kinase</th>
<th>Inhibitors</th>
<th>Role of Kinase in the Heart/Vasculature/Models Used</th>
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<tr>
<td>Abl</td>
<td>Imatinib/D/N bosutinib, etc</td>
<td>Inhibition of Abl by imatinib induced ER stress and cell death in cardiomyocytes19,22</td>
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<tr>
<td>Growth factor receptors</td>
<td></td>
<td></td>
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<tr>
<td>EGFR (ERBB1)</td>
<td>Gefitinib, erlotinib, lapatinib, XL647, BIBW-2992</td>
<td>Inhibition of EGFR by erlotinib led to reduced LV function under conditions of chronic catecholamine stimulation7</td>
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<tr>
<td>HER2 (ERBB2)</td>
<td>Lapatinib, XL647, BIBW-2992</td>
<td>Conditional deletion of ERBB2 led to DCM72</td>
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<td>c-Kit</td>
<td>Imatinib/D/N sunitinib, sorafenib vatalanib</td>
<td>c-Kit deficiency blocked: (1) homing of CSC to sites of post-MI injury67; 2) CSC differentiation65; and (3) cardiomyocyte terminal differentiation.68 Imatinib reduced stenosis after arterial injury65</td>
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<tr>
<td>VEGFRs</td>
<td>Sunitinib, sorafenib pazopanib, vandetanib, cediranib, vatalanib</td>
<td>VEGF trap37 or inhibition32 caused cardiac dysfunction after PO</td>
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<td>PDGFRs</td>
<td>Imatinib/D/N sunitinib, sorafenib pazopanib, vatalanib</td>
<td>Intramyocardial delivery of PDGF improved post-MI ventricular function72; deletion of PDGFR6 led to LV dysfunction after PO64</td>
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<tr>
<td>PI3K pathway</td>
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<tr>
<td>PI3K(p110α)</td>
<td>SF-1126, XL765</td>
<td>Mediates physiological heart growth and provides protection from pathological stress36</td>
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<tr>
<td>PI3K(p110γ)</td>
<td>SF-1126, XL765</td>
<td>Regulates contractility and pathological hypertrophy74,75</td>
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<tr>
<td>Akt</td>
<td>VQD-002, perifosine</td>
<td>Regulates cardiomyocyte growth, proliferation, survival and metabolism76–78; promotes CSC proliferation and expansion79; inhibits cardiac sarcolemmal Na(H)+/H(H) exchanger activity80</td>
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<tr>
<td>PDK1</td>
<td>UCN-01</td>
<td>A dual effector for cardiac cell survival and beta-adrenergic response39</td>
</tr>
<tr>
<td>Ras/Raf/MEK/ERK pathway</td>
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<tr>
<td>Raf-1/B-Raf</td>
<td>Sorafenib RAF-265</td>
<td>Conditional deletion/DN led to LV dilatation and HF after PO62,63; specific gain-of-function mutations cause an HCM phenocopy61</td>
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<tr>
<td>MEK1/2</td>
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<td>Regulation of cardiac hypertrophy and cell survival81</td>
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<td>Cell cycle regulation</td>
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<td>CDK</td>
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<td>Cardiomyocyte cell cycle control in normal development and in response to injury84,82</td>
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<td>Aurora kinases</td>
<td>AZD-1152</td>
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<tr>
<td>PLKs</td>
<td>BI2526</td>
<td></td>
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<tr>
<td>Others</td>
<td></td>
<td></td>
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<tr>
<td>mTOR</td>
<td>Temsirolimus, everolimus, sirolimus, deforolimus</td>
<td>Central regulator of cardiac cell growth/hypertrophy41,42; integrates energy/metabolic status</td>
</tr>
<tr>
<td>JAK2</td>
<td>Lestaertinib, CP-690550, TG101348</td>
<td>JAK2-STAT3 generally protective, especially in I/R injury, hypertrophy, and postpartum cardiomyopathy48,57</td>
</tr>
<tr>
<td>p38</td>
<td>GWB856553</td>
<td>p38 inhibition attenuated biomarkers of atherosclerosis69; reduced inflammatory burden in subjects already on statin therapy and undergoing PCI60</td>
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CSC indicates bone marrow–derived cardiac stem cell; DCM, dilated cardiomyopathy; D/N, dasatinib/nilotinib; DN, dominant-negative; ESC, embryonic stem cells; HCM, hypertrophic cardiomyopathy; HF, heart failure; I/R, ischemia/reperfusion; MI, myocardial infarction; PCI, percutaneous coronary intervention; PO, pressure overload.
Src family member Lck, CSF1R, Cdc2, anddiscoidin domain receptor (DDR)1 are all inhibited by imatinib, although c-Kit and Lck are not expressed in adult cardiomyocytes. Kerkela et al used the Abl (T315I) point mutant that renders the kinase resistant to imatinib to demonstrate rescue of cardiomyocyte death following gene transfer of T315I (but not wild-type) Abl (Figure 1). Thus, the T315I mutant was used as a tool to determine that imatinib-mediated inhibition of c-Abl induced ER stress and that this played a key role in driving cell death. Supporting this as the mechanism, Fernandez et al redesigned imatinib to no longer inhibit Abl, and cardiotoxicity was not seen with this agent in mouse models.11 Although the redesigned drug was obviously ineffective in treating CML (driven by Bcr-Abl), it was equally effective to imatinib in treating GIST models driven by c-Kit mutations. Thus, by knowing the mechanism of toxicity, and redesigning the drug accordingly, one could theoretically reduce cardio toxicity in GIST patients. However, the on-target toxicity of imatinib-mediated inhibition of Abl appears to be unavoidable in CML patients. Fortunately, this is not a major problem clinically, but as we will discuss, with other inhibitors in development for other cancers, including inhibitors of the PI3K pathway, on-target toxicity could be very problematic. Of note, the studies with imatinib are one example of the use of TKIs to identify novel biological functions of kinases in the heart- in this case, Abl-mediated maintenance of ER homeostasis (Figure 1).

Approaches to deal with unavoidable on-target toxicity have been proposed and include (1) targeted delivery of drug specifically to the cancer, sparing normal tissue (an area of obvious intense interest); and (2) inhibiting cell death pathways in the heart that are activated by a compound but that are not necessary for tumor cell death. For the latter, JNK inhibition has been proposed as a strategy to limit imatinib-induced cardiomyocyte death without reducing antitumor efficacy (Figure 1). At present, both of the above strategies are much more theoretical than real.12

**Off-Target Toxicity**

The second class of toxicity is off-target. In this case, a kinase not intended to be inhibited by the compound, plays

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**Figure 1.** Proposed signaling events in the ER stress response that mediate imatinib-induced cardiomyocyte toxicity. In cardiomyocytes, Abl maintains ER homeostasis by mechanisms that are not yet clear. The Abl inhibitor imatinib induces ER stress, leading to activation of the PKR-like ER kinase (PERK) and IRE1 (a dual protein kinase and endoribonuclease) and to increased expression of PKCα.10 PERK phosphorylates and inactivates the eIF2α (eukaryotic translation initiation factor 2α) as part of a protective response, shutting off general mRNA translation but selectively prompting the translation of certain mRNAs that encode ER chaperones, thereby reducing the unfolded protein load on the ER. The endoribonuclease activity of IRE1 splicesthe X-box–binding protein 1 (XBP1) mRNA, and the protein product induces expression of unfolded protein response (UPR) and ER-assisted degradation (ERAD) genes, leading to protein degradation and reduced ER protein load. On sustained ER stress, IRE1 activates apoptosis signal-regulating kinase 1 (ASK1), leading to c-Jun N-terminal kinase (JNK) activation, and: (1) phosphorylation of 14-3-3 proteins and release of Bax (BCL2-associated X protein), followed by cytochrome c release from mitochondria; and (2) inhibition of antiapoptotic Bcl-2 (B-cell leukemia/lymphoma 2) and activation of the proapoptotic family member Bim.19 Also with sustained stress, the transcription factor, C/EBP homologous protein (CHOP), is induced which inhibits Bcl-2 expression and induces Bim expression. ASK1/JNK and CHOP activation contribute to caspase activation and cell death. In cultured cardiomyocytes, inhibiting JNK protects against imatinib-induced cardiomyocyte toxicity. Furthermore, when the imatinib-resistant Abl mutant T315I was expressed in cardiomyocytes, imatinib failed to induce cell death, demonstrating that imatinib-mediated inhibition of Abl was key to the toxicity. The role, if any, of increased expression of PKCs in imatinib-induced cardiomyocyte toxicity is not known, although it is generally thought to mediate cellular injury in cardiomyocytes.
a key role in the heart. Often the kinase mediating the toxicity will not be known, and the complexity of identifying the key target, inhibition of which leads to cardiotoxicity, can be very difficult. This is made all the worse by multitargeting (as noted, sunitinib has ≥50 targets and sorafenib has ≥15).4 Furthermore, it is important to understand that not just kinases, but any enzyme that binds purines could also be inhibited. For example, imatinib has been shown to not only inhibit off-target kinases such as Cdc2 and DDR1 but also to inhibit the oxidoreductase NQO2 which plays a protective role in the cell’s response to oxidative stress (Figure 2).13 We illustrate off-target toxicity using sunitinib as an example.

As noted above, sunitinib led to cardiotoxicity in a significant percentage of patients. Although the pronounced hypertension induced by this agent20 almost certainly played a role in the LV dysfunction seen, this was likely an exacerbating factor rather than causal because some of the patients who developed LV dysfunction did not develop hypertension on sunitinib. Chu et al and Kerkela et al examined possible mechanisms of toxicity in cultured cardiomyocytes and found clear-cut evidence of energy compromise.20,24 Surprisingly, whereas this should have recruited AMP-activated protein kinase (AMPK), the master regulator of the response of the cardiomyocyte to energy stress, this did not occur in the sunitinib-treated cardiomyocytes. Kinase assays determined that sunitinib was a very potent direct inhibitor of AMPK with IC50 values for the catalytic (α) subunits in the very low nanomolar range, accounting for the failure to recruit the kinase.24 Adenoviral-mediated gene transfer of a constitutively active α subunit of AMPK partially rescued sunitinib-induced cell death, suggesting off-target inhibition of AMPK accounted, at least in part, for the toxicity.

This example illustrates off-target kinase inhibition that may be dispensable for tumor cell killing but is important for metabolic homeostasis in the heart. As a caveat, however, AMPK has been proposed to be central to the adaptation (and survival) of not only hypoxic/energy-deprived cardiomyocytes but also energy-deprived cancer cells located in hypoxic regions of solid tumors.25 Thus inhibition of AMPK might be key to effective treatment of cancers and could account, in part, for some of the success of sunitinib in solid tumors. More recently, Korenykh et al reported the surprising finding that several kinase inhibitors, including sunitinib, can directly activate the endoribonuclease activity of IRE1, leading to XBP-1 splicing and a reduction in ER stress.26 This response can be expected to be cytoprotective for both stressed cancer cells and cardiomyocytes. Although the authors suggested that sunitinib be redesigned to no longer activate the endoribonuclease activity, thereby enhancing cancer cell death, this might enhance cardiotoxicity. These examples again highlight the similar critical roles played by many of these kinases in cancer progression and cardioprotection.

What Causes LV Dysfunction With TKIs and Is It Reversible?
Although it has been possible to implicate critical kinases, inhibition of which lead to cardiotoxicity, it remains unclear whether LV dysfunction with TKIs is attributable to myocyte loss (and therefore largely irreversible) or myocyte dysfunction (potentially reversible). Neurons and cardiomyocytes appear to be quite resistant to apoptosis induced by cytochrome c release and caspase activation. Contributing to this is the decreased expression of Apaf1 that is directly linked to the tight regulation of caspase activation by endogenous XIAP.27 Consistent with this, we did not see an increase in apoptosis in mice treated with sunitinib until we exposed the mice to a pressure load induced by infusion of phenylephrine via implanted minipump, and even then, the increase, although statistically significant, was modest.28 In contrast, we saw clear evidence of opening of the mitochondrial permeability transition pore in the mice as evidenced by marked mitochondrial swelling and destruction of the normal mitochondrial architecture.20 Strikingly, we saw a very similar picture in transmission electron micrographs of an endomyocardial biopsy obtained from a patient who presented with advanced heart failure while receiving sunitinib.20,24 This picture could be consistent with LV dysfunction being secondary to impaired energy generation, with or without cell death by so-called programmed necrosis. Finally, a recent study with adult rat ventricular myocytes showed that the inhibition of ErbB2 by PKI1166, did not induce necrosis or apoptosis but caused myofibrillar structural damage and inhibited excitation-contraction coupling.29 Although, to our knowledge this has not been described with any TKIs, if present, this could contribute to LV dysfunction.

It is clear that TKI-induced LV dysfunction can normalize after withdrawal of drug and/or institution of standard heart failure therapy,20 but this is not a universal response.30 Furthermore, whether any reversibility of LV dysfunction is accompanied by reversibility of injury at the myocyte level, and whether it will be long-lasting, remains unclear. With that said, in the patient noted above, there was very striking reversibility at the myocyte level with marked restoration of mitochondrial number and integrity after withdrawal of sunitinib.24

One final note on mechanisms of cardiotoxicity of VEGFR inhibitors is that a number of studies in mouse models have suggested that angiogenesis is key to maintaining cardiac homeostasis in response to pressure overload31,32 and ischemia,33 and this, taken together with the significant hypertension induced by VEGFR inhibitors, might explain the LV dysfunction seen with sunitinib. However, reported rates of LV dysfunction with sorafenib and bevacizumab (a monoclonal antibody that functions as a VEGF trap) are significantly lower than with sunitinib. The higher cardiotoxicity rates reported for sunitinib could be attributable to a variety of reasons including more potent inhibition of VEGFRs, different patient selection (comorbidities, prior treatments), or better ascertainment of dysfunction resulting from closer follow-up, but, if true, more likely reflects an intrinsic difference between the agents attributable to off-target inhibition of other critical kinases by sunitinib (eg, AMPK).

Reading the Tea Leaves: Can We Predict Future Problematic Agents?
In this section, we take a target-based approach to highlight novel targets that are the present focus of drug development
in cancer and will use studies previously done in various models to raise concerns about kinase inhibitors targeting these kinases. Predicting problematic agents based on studies with gene-targeted mice can give valuable information, especially when combined with pathway analysis programs (eg, Jubilant [http://www.jubilantbiosys.com], ToxWiz [http://www.cancellnet.com], Ingenuity [http://www.ingenuity.com]). However, kinase inactive knock-ins probably would predict phenotypes better than knockouts because, for example, any scaffolding functions of the kinase would be preserved (as they likely would with drug treatment), unlike in the knockout. In addition, because drugs never inhibit their targets 100%, both the knockout and kinase-dead knock-in would likely have more severe phenotypes than any drug targeting the kinase of interest. With those caveats noted, we will proceed to examine a few key cancer targets that raise significant concerns for the heart.

The PI3K Pathway: Roles in Cancer and the Heart

Probably the most active drug development in cancer is directed at the many components that make up the PI3K pathway, and therefore we discuss this pathway, the potential implications for the heart of targeting it in cancer, and where drug development in this area stands. The PI3K pathway is very notable in that all of the major factors in the pathway have been found to be mutated or amplified in a wide range of cancers, making this pathway an ideal target in cancer therapy. Furthermore, Yuan and Cantley, in an elegant review of theories of cancer treatment, proposed that redundant activation of the PI3K pathway by multiple mutations or amplifications of pathway components (ie, redundancy), combined with activation of multiple nonoverlapping pathways will, with the exception of the rare cancer that is truly oncogene-addicted to a single mutated kinase, require combination therapy. For example, one could simultaneously target PI3K, Akt, and mTOR (mammalian target of rapamycin), in addition to mutated RTKs (Figure 3). Although this is undoubtedly true, with the central role played by the PI3K pathway in cardiomyocyte survival in the setting of stress, in insulin sensitivity, and in physiological growth (driven by p110α), concerns over aggressively targeting this pathway are obvious.

The PI3K pathway is immediately downstream (and is a critical mediator) of cellular responses initiated by mutated or amplified RTKs in cancer. These include insulin-like growth factor receptor, epidermal growth factor receptor, human epidermal growth factor receptor 2, Kit, PDGFRs, and Met, which are dysregulated in a host of cancers (Table 2). The p110α isoform of PI3K is also commonly mutated in breast (27%), endometrial (23%), and other cancers. Three missense mutations, which are in the kinase and helical domains of p110α, lead to constitutive activation of the kinase. p110α is also amplified in a variety of solid tumors.

PTEN (phosphatase and tensin homolog deleted on chromosome 10) is a tumor suppressor phosphatase that dephosphorylates the 3' residue of PIP3 (phosphatidylinositol 3,4,5-trisphosphate), counteracting p110α (and other PI3K isoforms), thereby blocking activation of Akt. Germline mutations in PTEN cause hamartoma tumor syndromes, and sporadic somatic missense mutations are common in a wide variety of tumors. Loss of one allele of PTEN significantly contributes to tumor growth in the setting of other mutations. The critical role played by PTEN versus the PI3K/Akt pathway in tumorigenesis is highlighted by the fact that PTEN is second only to p53 as the most frequently affected tumor suppressor in cancers and this is particularly true in solid tumors. Of note, the effects of PTEN are not solely attributable to inhibition of the PI3K/Akt pathway because...
PTEN has additional critical roles that include regulation of p53 stability and maintenance of genome stability via effects at the centromere.35

Amplifications in all 3 of the Akt isoforms, as well as a common missense (E17K) mutation in the PH domain of Akt1 that leads to constitutive association with the cell membrane, and constitutive activation, have been identified in a variety of cancers. In mouse models, this mutation leads to leukemia. Of equal, if not greater, importance, Akt is potently activated by all of the mutations noted above, and is also strongly activated by mutations of Ras (particularly prevalent in colorectal cancer). Akt is key for the survival of many cancer cells via inhibitory effects on the intrinsic apoptosis pathway (Bad and FOXO3).

Not surprisingly, there has been a great deal of activity in the pharmaceutical industry to identify agents that target the PI3K pathway, and several agents are currently in clinical trials.18,34 Indeed the scaffolds of the well-known PI3K inhibitors, wortmannin (an irreversible inhibitor that forms a covalent bond with a key residue of the kinase) and LY294002 (a typical small molecule ATP-competitive inhibitor) were used as starting points to identify agents with superior pharmacokinetic properties. These newer agents typically inhibit all 4 class I PI3K isoforms including p110α (the relevant target in cancer), -β, -γ (a regulator of pathological hypertrophy), and -δ. Many of these agents (eg, SF-1126, which is currently in phase 1 trials, and XL765) also inhibit other members of the extended PI3K family including DNA-PK (a key regulator of repair of DNA double strand breaks, especially occurring after ionizing radiation) and mTOR. Obvious concerns over cardiotoxicity exist for this class of compounds,36 and it is the hope that p110α mutation-selective inhibitors can be made which would not inhibit wild-type p110α. Although possible, these mutations are not near the ATP pocket and, as noted, this presents a major challenge for drug design.34 Ultimately, however, we believe this may be necessary to avoid significant cardiotoxicity.

Akt has also been a major target of drug development. One compound, OSK690693, an ATP-competitive inhibitor, entered clinical trials, but one trial was withdrawn and another was terminated, although the reasons were not stated. This inhibitor also inhibited other members of the AGC kinase family (protein kinase [PK]A, PKG, and PKC), as well as the CAMK [calmodulin-dependent protein kinase] family. Allosteric inhibitors would be more selective (and likely less toxic), but, unfortunately, they appear to be less potent against the constitutively active E17K mutation identified in breast and other cancers.34 As with p110α inhibition, the critical role of Akt in cardiomyocyte survival in the setting of stress raises serious concerns over the use of these agents in patients with cardiovascular comorbidities.

Phospholipid-dependent kinase (PDK)1 is another potential target in this pathway. It is particularly attractive from an oncological perspective because it is upstream of a number of progrowth kinases in addition to Akt, including S6K, SGK [serum/glucocorticoid regulated kinase], PKCs, and ribosomal S6 kinase (RSKs), and, unlike many other kinases in this pathway, there is only one isoform. This, and the fact that inhibition of PDK1 prevents tamoxifen resistance in breast cancer cells, make it a kinase of significant interest. Furthermore, it is constitutively active, making it both important to inhibit and straightforward to do so with ATP-competitive inhibitors. Although mutations in PDK1 promoting cancer have not been described, because PDK1 is necessary for phosphorylation of the key T308 residue of Akt, inhibition could reduce Akt activity even in the E17K PH domain mutant. Compounds targeting PDK1 are in development and one, UCN-01 (a compound based on the structure of staurosporine which, not surprisingly, has poor selectivity), has been used in clinical trials. Of note, the compound induced insulin resistance, which could be attributable to downstream inhibition of Akt. Another drug targeting PDK1 that has been used in clinical trials (phase 2 and 3) is the cyclooxygenase-2 inhibitor celecoxib. It competes for binding to the ATP pocket, and although a relatively weak inhibitor, more active compounds have been derived.

The PDK1 KO mouse dies prematurely as a result of heart failure with thinned ventricular walls, smaller myocytes, and depressed LV function.37 Lawlor et al studied a germline hypomorphic PDK1 KO (10% of normal levels of PDK1) and reported that the mice were 40% to 50% smaller than controls, including the heart, and this was attributable to inability of myocytes to undergo physiological hypertrophy.38 More recently, conditional deletion of PDK1 in the heart identified key roles in coordinating both cardiomyocyte survival and responsiveness to β-adrenergic stimulation. PDK1 deletion led to profound heart failure.39

The PI3K/Akt pathway converges on mTOR, which is a central regulator of cell growth, including cardiomyocyte growth, acting by regulating the protein translation machinery (mTOR complex 1 or mTORC1) and Akt phosphorylation at Ser473 (mTORC2; Figure 3).40 Indeed, mTOR is a convergence point for progrowth pathways (including not only PI3K/Akt but also the Ras-Raf-ERK-RSK pathway, which activate mTOR), and antigrowth pathways including AMPK and GSK-3, as well as hypoxia, energy deprivation, and reduced abundance of amino acids (all of which inhibit mTORC1 via activation of the tuberous sclerosis [Tsc1/2] complex; Figure 3). Thus, mTOR is activated in response to progrowth stimuli and is inhibited in response to withdrawal of growth factors or energy depletion. Of note, cancer cells in which PTEN is inactivated (and, therefore, Akt and mTOR are activated) are sensitized to cell death following rapamycin-mediated inhibition of mTORC1, suggesting that the survival of cancer cells harboring PTEN mutations is dependent on intact mTOR signaling. Furthermore, deletion of PTEN in the hematopoietic system resulted in acute myeloid leukemia, and rapamycin led to a marked reduction in leukemic burden.

Although mutations in mTOR do not appear to drive transformation, and inhibitors of mTOR will typically be used in combination with inhibitors of other kinases in the pathway, the position of mTOR as a central clearinghouse that integrates progrowth signals makes it a very attractive target. Consistent with this, the mTOR inhibitors, temsirolimus (Torisel), everolimus (Afinitor), and sirolimus (Rapamune) are being evaluated for anticancer efficacy in
hundreds of clinical trials and are approved for treatment of advanced renal cell carcinoma (http://www.cancer.gov/cancertopics/druginfo/fda-temsirolimus). These agents complex with FKBP-12, thereby inhibiting mTORC1 activity. The mTOR inhibitors are now being tested in combination with sunitinib and sorafenib in renal cell carcinoma.

This PI3K/PDK1/Akt/mTOR/S6K system, more than any other, epitomizes the similarity between cancer signaling and hypertrophy/survival signaling in cardiomyocytes. Although mTOR inhibitors have been relatively well-tolerated long-term in transplant patients and have shown beneficial effects in experimental models of hypertrophy, there are concerns that when used in combination with therapeutics targeting other components of the pathway, the inability of mTOR to respond appropriately to the energy status of the cardiomyocyte will enhance toxicity. We believe that nowhere will the careful selection of patients and close follow-up be more important than with agents targeting the PI3K pathway.

**Cell Cycle Regulators: CDKs, Polo-Like Kinase, and Aurora Kinases**

Targeting cell cycle regulators is a major focus in cancer. From a cardiac perspective, it seems that inhibiting kinases involved in cell cycle regulation might be well tolerated because cardiomyocytes are generally viewed as terminally differentiated. However, data challenging this concept are well known, including a recent study which used C14 dating to conclude that 1% of cardiomyocytes turnover annually in people at the age of 25 years, dropping to 0.45% at the age of 75 years. Despite this low annual turnover rate, it was estimated that fully 55% of myocytes in the adult heart were from new myocyte formation that occurred after birth. Furthermore, proliferation of any cardiac-resident stem cell populations or bone marrow–derived cardiac stem cells, which has been reported to increase significantly in the setting of stress, would almost certainly be inhibited by inhibitors targeting the critical Cdks: Cdk2, -4, -6 (the interphase Cdks), and Cdk1 (Cdc2, the mitotic Cdk). Although a recent study shed some light on a cardioprotective role for Cdk2 inhibition in vivo during ischemia/reperfusion injury, in general, the consequences of Cdk inhibition in the adult heart are simply not clear.

Possibly of more (at least theoretical) concern is inhibition of the mitotic regulators of the Aurora and polo-like kinase (PLK) families. Aurora kinases A and B control chromosomal alignment and segregation during mitosis and are required to preserve genomic stability. Both regulate the spindle assembly checkpoint. Inhibition of Aurora B abrogates the spindle assembly checkpoint, resulting in inappropriate M phase progression, polyploidy, and eventually apoptosis or senescence. PLK1 (by far the best understood member of the family) activates the CDK1–cyclin B complex at the G2-to-M phase transition and is necessary for spindle formation, chromosome segregation, and cytokinesis. Inhibition of PLK1 induces prolonged mitotic arrest and subsequent apoptosis. Numerous Aurora and PLK inhibitors are in development with several in clinical trials.

Why should inhibition of Aurora and PLK be of concern in the heart? Whereas the importance of cardiomyocyte and cardiac stem cell proliferation continues to be debated, DNA duplication in cardiomyocytes, followed by karyokinesis with or without cytokinesis, is a well-described phenomenon that, at least in animal models, is increased in the setting of stress. Both karyokinesis and cytokinesis will be dysregulated by agents targeting Aurora and PLK. Furthermore, when M phase is disrupted, the cell typically undergoes apoptosis. With this backdrop, there is some cause for concern about even these agents that target kinases that would seem to be dispensable in the heart.

**Kinase Inhibitors for Other Disease States**

Small molecule kinase inhibitors are also in development for diseases in addition to cancer. In this section, we will briefly review these agents, focusing on their real or potential uses for the treatment of cardiovascular diseases.

**Inflammatory Diseases**

**p38 Mitogen-Activated Protein Kinase Inhibition**

Initial efforts to develop kinase inhibitors to treat inflammatory diseases focused on the p38 mitogen-activated protein kinase (MAPK) after it was discovered to be a key enzyme in the biosynthesis of the proinflammatory cytokines tumor necrosis factor-α and interleukin-1β. Although p38 MAPK was expected to be an ideal target for the treatment of chronic inflammatory diseases such as rheumatoid arthritis, several well-established pyridinyl-imidazole inhibitors of p38 showed liver toxicity in animal studies. Nevertheless, attempts have been made to use p38 MAPK inhibitors for cardiovascular disease because chronic inflammation is believed to contribute to the pathogenesis. Recent preclinical studies demonstrated that a specific p38 MAPK inhibitor, SB-239063, prevented endothelial dysfunction, blunted angiotensin II-induced hypertension and cardiac hypertrophy, and attenuated atherosclerotic plaque inflammation. More recently, data were presented showing that when a p38 MAPK inhibitor was given at low doses over 3 months to patients with cardiovascular disease who were already receiving statin therapy, C-reactive protein declined and vascular reactivity improved. Another p38 MAPK inhibitor, GW856553, has entered a phase 2 clinical trial in patients with acute coronary syndrome (http://clinicaltrials.gov/ct2/show/NCT00910962?term=solstice&rank=1). These studies support further investigation into the potential role of p38 MAPK inhibitors as a therapeutic strategy for atherosclerotic disease.

**JAK/STAT Inhibition**

Janus kinase (JAK) inhibitors, a new class of immunosuppressive drugs, are being extensively studied in various disease states. There are four JAKs (Jak1, Jak2, Jak3, and Tyk2), which respond to numerous cytokines and transmit signals from cytokine receptors to the downstream STAT proteins. Selective Jak3 inhibitors have been proposed to be superior to cyclosporine and corticosteroids in the treatment of autoimmune diseases and transplant rejection. A novel Jak3 inhibitor, CP-690550, is in clinical trials for rheumatoid
arthitis, psoriasis, Crohn’s disease and renal transplant rejection.51

In the cancer field, interest in Jak2 has been driven by the findings that human myeloproliferative disorders such as polycythemia vera, essential thrombocytosis, and idiopathic myelofibrosis are associated with activating mutations in Jak2. Most myeloproliferative disorder patients carry an activating point mutation (V617F), which appears to act at least in part by activating STAT3 and STAT5 in leukemic cells, leading to cytokine hypersensitivity and enhanced proliferation.52 Among various Jak2 inhibitors that are in clinical trials for myeloproliferative disorders, lestaurtinib and dasatinib have been reported to have activity against mutated Jak2 and are under evaluation for treatment of polycythemia vera. Recently, selective Jak2 inhibitors TG101348,53 and CP-690550,54 which have relatively little activity against wild type Jak2 but show stronger activity in cells with mutated Jak2, were tested in preclinical models for V617F-induced polycythemia vera and demonstrated efficacy. These agents will likely advance to clinical trials.

Despite the potential of JAK inhibition for the treatment of immunologic diseases and myeloproliferative disorders, JAK/STAT signaling is generally believed to be protective in the heart, where 3 JAKs (JAK1, JAK2, and Tyk2), but not JAK3, and all 7 STAT proteins are present.55 The protective role of JAK-STAT signaling in the heart has been extensively reviewed,56,57 especially the role of Stat3 in ischemia/reperfusion injury, hypertrophy, and postpartum cardiomyopathy. These pleiotropic roles of JAK/STAT signaling in the heart raise some concerns and, going forward, these agents will need to be watched.57

Diabetes: Type 1 Autoimmune Diabetes Mellitus
In addition to its antitumor effects, imatinib has been shown to have antiinflammatory effects in various mouse models.14,58 Indeed, case reports and phase 1 studies in humans have demonstrated a positive effect of imatinib on several autoimmune diseases such as rheumatoid arthritis and psoriasis. Moreover, imatinib was recently reported to improve type 1 autoimmune diabetes mellitus (T1D) in nonobese diabetic mice, apparently by inhibiting PDGFR because specific neutralization of PDGF reversed T1D (Figure 2).58 Among various Jak2 inhibitors that are in clinical trials for myeloproliferative disorders, lestaurtinib and dasatinib have been reported to have activity against mutated Jak2 and are under evaluation for treatment of polycythemia vera. Recently, selective Jak2 inhibitors TG101348,53 and CP-690550,54 which have relatively little activity against wild type Jak2 but show stronger activity in cells with mutated Jak2, were tested in preclinical models for V617F-induced polycythemia vera and demonstrated efficacy. These agents will likely advance to clinical trials.

In conclusion, drug development in the cancer arena has produced an explosion of new agents. At this point in time, preclinical testing is unable to accurately identify all (or maybe even most) agents that may have versus will not have associated cardiotoxicity. With a thorough knowledge of the spectrum of kinases inhibited by a specific inhibitor, and where possible the role the targeted kinases play in the heart, to studying the biology of various stem cell populations. We believe that this will become an important use of these agents as we try to divine the role of the ~250 kinases for which biological functions are unknown.

Post–Arterial Injury Restenosis
Several studies suggest that TKIs might also have therapeutic potential for restenosis after vascular injury/percutaneous coronary intervention (Figure 2). One such study showed that imatinib administered after femoral artery injury reduced intimal hyperplasia, and this was attributed to the inhibition of c-Kit in progenitor cells and consequent prevention of their homing to the injured vascular wall and differentiation to smooth muscle cells.65 Additionally, in a balloon injury model of the rat carotid artery, imatinib inhibited intimal hyperplasia and arterial stenosis in a dose-dependent manner without blocking endothelial cell repair, an adverse effect of drug eluting stents.66 This effect of imatinib was presumed, but not proven, to be mediated by inhibition of PDGFR signaling. On the other hand, c-Kit-deficient mice demonstrated worsened post–myocardial infarction remodeling and reduced cardiac function.67 Furthermore, c-Kit is required in vivo for cardiac stem cell and cardiomyocyte differentiation.68 Therefore, although agents targeting c-Kit and PDGFRs might be used to reduce restenosis after arterial injury, they might have detrimental effects in the context of post–myocardial infarction remodeling or pressure stress.

Use of Agents to Identify Novel Functions of Kinases in the Heart: Chemical Genetics
The biological functions of many kinases in the heart are entirely unclear. The availability of TKIs with excellent pharmacokinetic and pharmacodynamic properties sets up the possibility of defining these roles, with the major limitation again being poor selectivity. However, by using combinations of inhibitors that all inhibit the kinase of interest, but that have different off-target selectivity profiles, one can identify specific roles played by the kinase of interest. Applications could be in anything from the adult heart, to the developing heart, to studying the biology of various stem cell populations. We believe that this will become an important use of these agents as we try to divine the role of the ~250 kinases for which biological functions are unknown.
available commercial platforms is approximately half of the kinome), but this is a deficit that should be corrected shortly; (2) lack of knowledge concerning the role played by many kinases in the heart (a deficit that will not be corrected rapidly); and (3) lack of an understanding of what role prior or concurrent therapy with traditional chemotherapeutics plays in cardiotoxicity. Thus, there will continue to be surprises, but presumably over time, the number of surprises will shrink to manageable numbers. With (1) advances in drug design, 2) greater awareness of the problem, (3) better cooperation among clinical and basic cardiologists and oncologists and the pharmaceutical industry in the early phases of drug development, and (4) better preclinical screening approaches, we believe cardiotoxicity of cancer therapeutics will become a very manageable problem. There will, however, continue to be unavoidable instances of cardiotoxicity because of the similar pro-survival roles the kinases play in both cancer cells and cardiomyocytes. It will be essential to identify effective strategies to address this central issue of on-target toxicity.

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