Emerging Paradigms in Cardiomyopathies Associated With Cancer Therapies
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Abstract—The cardiovascular care of cancer patients (cardio-oncology) has emerged as a new discipline in clinical medicine, given recent advances in cancer therapy, and is driven by the cardiovascular complications that occur as a direct result of cancer therapy. Traditional therapies such as anthracyclines and radiation have been recognized for years to have cardiovascular complications. Less expected were the cardiovascular effects of targeted cancer therapies, which were initially thought to be specific to cancer cells and would spare any adverse effects on the heart. Cancers are typically driven by mutations, translocations, or overexpression of protein kinases. The majority of these mutated kinases are tyrosine kinases, though serine/threonine kinases also play key roles in some malignancies. Several agents were developed to target these kinases, but many more are in development. Major successes have been largely restricted to agents targeting human epidermal growth factor receptor-2 (mutated or overexpressed in breast cancer), BCR-ABL (chronic myelogenous leukemia and some cases of acute lymphoblastic leukemia), and c-Kit (gastrointestinal stromal tumor). Other agents targeting more complex malignancies, such as advanced solid tumors, have had successes, but have not extended life to the degree seen with chronic myelogenous leukemia. Years before the first targeted therapy, Judah Folkman correctly proposed that to address solid tumors one had to target the inherent neoangiogenesis. Unfortunately, emerging evidence confirms that angiogenesis inhibitors cause cardiac complications, including hypertension, thrombosis, and heart failure. And therein lies the catch-22. Nevertheless, cardio-oncology has the potential to be transformative as the human cardiomyopathies that arise from targeted therapies can provide insights into the normal function of the heart. (Circ Res. 2013;113:754-764.)

Key Words: angiogenesis inhibitors ■ anthracyclines ■ cancer ■ chemotherapies ■ cardiomyopathy ■ cardio-oncology ■ HER2-targeted therapies
Cardiomyopathies and Targeted Cancer Therapies

There has been an explosion in cancer drug development during the past 2 decades. An early so-called targeted agent, trastuzumab, that targets Her2 (human epidermal growth factor receptor-2), which is mutated or overexpressed, in about 20% of breast cancers. It was approved in 1998 with the hope that trastuzumab would have few side effects because of the selectivity of the antibody and of data in early clinical studies showing minimal serious adverse events. However, this turned out not to be the case, with a significant incidence of left ventricular (LV) dysfunction, especially when combined with anthracyclines. Subsequently, significant cardiotoxicity with LV dysfunction and chamber dilatation was seen in mice with a cardiac-specific deletion of the Her2 gene, confirming a central role of Her2 in maintaining cardiac homeostasis. In this review, we will attempt to shed light on the molecular mechanisms driving the cardiotoxicity seen with an ever-increasing number of Her2-targeted agents.

A number of reviews have been published on this topic, and the reader is urged to read those by way of background, because herein we will focus on recent findings, particularly on (1) novel molecular mechanisms underlying anthracycline cardiotoxicity; (2) mechanisms of cardiotoxicity of what seems to be the most problematic class of agents targeting vascular endothelial growth factor (VEGF) and VEGF receptors (VEGFRs); (3) a surprising toxicity (severe pulmonary hypertension) with dasatinib, an agent that has been in use for several years; (4) potential concerns over nilotinib and ponatinib, a derivative of imatinib, in possibly promoting peripheral vascular disease; and (5) the other side of the Her2 coin—the potential of developing novel biomarkers of cardiotoxicity and of using ligands of the Her2 receptor (neuregulins [NRG]) to not only better understand mechanisms of cardiotoxicity, but also to treat patients with heart failure (HF). It is hoped that this update will pique the interest of HF physicians and lead them to learn more about these unique and fascinating forms of HF that tell us much about the critical pathways regulating cardiac homeostasis.

**Novel Mechanisms of Anthracycline Cardiotoxicity Are Identified**

Since the successful introduction of daunorubicin in the early 1950s, anthracyclines continue to be the most commonly used chemotherapeutic agents. The chemical structure of anthracyclines consists of a tetracyclic aglycone linked to an amino sugar, daunosamine. The chemical structure of doxorubicin differs from daunorubicin only by a single hydroxyl group but has somewhat distinct patterns in metabolism, pharmacokinetics, and spectrum of antitumor activity. The original article describing daunorubicin’s antitumor activity reported HF as a potential complication. Importantly, patients can develop HF years later to several hundred times greater concentrations than in the extracellular compartment. The redox cycling of anthracyclines can generate a large amount of intracellular superoxide radicals. Accumulation of free iron can lead to DNA damage and lipid peroxidation by converting $O_2^-$ and $H_2O_2$ into hydroxyl radical (OH·), one of the most potent oxidants, contributing to oxidative stress and cytotoxicity. Anthracyclines cause uncoupling of the electron transport chain in the mitochondria, impairing oxidative phosphorylation and ATP synthesis, making cells more vulnerable to ROS.

A variety of antioxidants have been studied in animal models and clinical trials, including probucol, vitamin E, and...
and N-acetylcysteine. However, these have failed to provide cardioprotection against anthracycline chemotherapy. The only Food and Drug Administration (FDA)–approved agent for preventing cardiomyopathy associated with anthracycline chemotherapy is dexrazoxane, a neutral prodrug analog of the tetraacid metal chelator EDTA. The initial proposed mechanism for its cardioprotective effect was the iron-chelating property similar to EDTA. Dexrazoxane quickly distributes intracellularly to remove Fe$^{3+}$ from the Fe$^{3+}$–anthracycline complex or binds to free iron in the cell, thus reducing the production of ROS. However, other iron-chelating agents such as deferasirox and bisdioxopiperazine failed to provide cardioprotection against doxorubicin in mouse models.

The failure of antioxidant or Fe chelation to ameliorate anthracycline-induced cardiotoxicity further emphasized the critical need for a new paradigm and understanding of doxorubicin cardiotoxicity. An important clue came from the ability of dexrazoxane to interfere directly with the formation of topoisomerase 2 (Top2) cleavage complexes raising the intriguing possibility that the cardioprotective effect of dexrazoxane was dependent on its ability to inhibit Top2. Indeed, anthracyclines are Top2 poisons. Top2 is a crucial enzyme in DNA transcription, replication, and recombination by transiently breaking the DNA backbone to allow DNA strands to pass through one another and untangle the supercoiled DNA complex. As an intercalating agent, a planar aglycone moiety of anthracycline inserts between adjacent DNA base pairs and forms a ternary Top2–doxorubicin–DNA cleavage complex. The formation of anthracyclines with the DNA complex inhibits the religation of the broken DNA strands, leading to DNA double strand breaks and cell death. There are 2 types of Top2 isozymes: Top2$\alpha$ and Top2$\beta$. These 2 isoforms are encoded by different genes with variable tissue expression. Top2$\alpha$ expression level is higher in proliferating tissues, including bone marrow, spleen, and tumor cells. In contrast, Top2$\beta$ is widely distributed in quiescent or terminally differentiated tissue, such as brain or liver. Interestingly, adult mammalian cardiomyocytes only expressed Top2$\beta$, but not Top2$\alpha$. Previously, it was shown that doxorubicin-induced DNA double strand breaks were greatly reduced in Top2$\beta$ knockout mouse embryonic fibroblasts when compared with Top2$\beta$ wild type. Thus, Top2$\beta$ may play an important role in anthracycline-induced cardiotoxicity.

To test the hypothesis that Top2$\beta$ was critical to anthracycline-induced cardiotoxicity, a conditional, cardiomyocyte-specific Top2$\beta$ knockout mouse (Top2$\beta^{-/-}$) was generated. These mice had no identifiable abnormalities at 10 months of age and ejection fraction (EF) was preserved, suggesting that Top2$\beta$ is not required in the nonstressed adult heart. However, following acute challenge with a relatively high single dose of doxorubicin, hearts from Top2$\beta^{-/-}$ mice had a marked reduction in DNA double strand breaks and apoptotic nuclei as compared with wild type. Thus, Top2$\beta$ alone is a key driver of cell death resulting from doxorubicin administration.

If Top2$\beta$ in cardiomyocytes is sufficient for doxorubicin to induce DNA double strand breaks and apoptosis, is there still a role for the ROS hypothesis? Of note, generation of ROS was reduced by 70% in doxorubicin-treated Top2$\beta^{-/-}$ mice as compared with Top2$\beta^{+/+}$ mice. Striking ultrastructural changes were also present in doxorubicin-treated wild-type mice, including mitochondrial damage and vacuolization. Oxygen consumption rate was significantly reduced in doxorubicin-treated wild-type mice, but not in Top2$\beta^{+/+}$ mice, consistent with mitochondrial dysfunction. Expression of genes involved in mitochondrial oxidative phosphorylation pathways were downregulated in Top2$\beta$ wild type, but not Top2$\beta^{-/-}$ mice. In addition, quantitative polymerase chain reaction analysis showed downregulation of PGC-1$\alpha$ and PGC-1$\beta$ transcripts. Given their crucial role in regulating cellular energy metabolism and mitochondrial biogenesis, this may be a key mechanism driving cardiotoxicity. The reduction of peroxisome proliferator-activated receptor-γ coactivator-1$\alpha$ also led to a decrease in the critical antioxidant, superoxide dismutase, possibly explaining in part the increase in ROS formation after anthracycline treatment. These data suggest that ROS generation after anthracycline treatment is a result of a change in the transcriptome affecting mitochondria and oxidative phosphorylation rather than redox cycling of doxorubicin as previously proposed.

Finally, the effect of longer-term doxorubicin administration on LVEF, mimicking the clinical scenario more closely, showed no significant change in LVEF after chronic administration of doxorubicin in Top2$\beta^{-/-}$ mice. In contrast, EF deteriorated significantly in wild-type mice. These results support the critical concept that doxorubicin-induced cardiotoxicity is mediated by Top2$\beta$ in cardiomyocytes.

The elucidation of the molecular mechanism of anthracycline-induced cardiotoxicity could be useful for predicting and preventing LV dysfunction. For example, developing Top2$\alpha$–specific drugs that have no Top2$\beta$ activity could be myocardial-sparing. This is predicated on the assumption that Top2$\beta$ does not have a major role in doxorubicin’s anticancer effects. One might also be able to use Top2$\beta$ expression level to stratify risk of developing anthracycline-induced cardiotoxicity. Thus, patients with low Top2$\beta$ expression in the heart could be less susceptible to anthracyclines. It has been reported that Top2$\beta$ levels in peripheral blood are correlated with the apoptotic response of leukocytes to doxorubicin in humans. Hence, the Top2$\beta$ level in peripheral blood may be useful as a surrogate marker for susceptibility to anthracycline-induced cardiomyopathy. However, this remains to be proven in clinical studies. Clearly, if we are able to predict which patients are more susceptible to anthracycline-induced cardiotoxicity before treatment, oncologists could select a less cardiotoxic drug, monitor the patient more closely, or provide early cardiac protection with dexrazoxane. Currently, angiotensin-converting enzyme

![Figure 1. Schematic of the mechanisms of doxorubicin-mediated cardiomyopathy. See text for details.](http://circres.ahajournals.org/)

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inhibitors or β-blockers have been recommended for cardioprotection after detection of cardiotoxicity through biomarkers or with a clear decrease in EF.\textsuperscript{40} The identification of the molecular basis of anthracycline-induced cardiotoxicity seems to be 1 more example in an age where genetic profiling could be used to provide personalized cardiac protection similar to the concept of personalized cancer therapy.

**A Remarkable Beginning for Small-Molecule Kinase Inhibitors**

Imatinib, the first small-molecule kinase inhibitor to reach the market, revolutionized the treatment of patients with chronic myelogenous leukemia. Imatinib inhibits the kinase activity of the BCR/Ab1 fusion protein that arises from the balanced translocation that creates the Philadelphia chromosome. This accounts for the vast majority of cases of chronic myelogenous leukemia and about 20% of cases of acute lymphoblastic leukemia. Imatinib is generally well tolerated, and because treatment is lifelong, that is critical.

The success of imatinib led to the development of similar agents targeting chronic myelogenous leukemia—nilotinib and dasatinib, and hopes were high that toxicity would be uncommon with these as well. In large part, that has been the case, but concerns have recently surfaced. Most notably, a group in France identified significant pulmonary hypertension in some chronic myelogenous leukemia patients treated with dasatinib. Although this side effect seems to be uncommon, dasatinib has been largely relegated to third-line treatment in France and is primarily used after failure with imatinib and nilotinib.

Less clear but of concern, several recent abstracts and articles (eg, Le Coutre et al\textsuperscript{42}) suggested that nilotinib might increase risk of peripheral vascular disease. Although not definitive, and mechanisms are entirely unclear, this may be one more example of the unpredictability of kinase inhibitors.

Why might dasatinib use be associated with pulmonary hypertension, whereas imatinib use is not? The most likely answer is that dasatinib is a promiscuous kinase inhibitor, inhibiting many more kinases than imatinib. If any of these kinases play a key role in the heart, cardiotoxicity could result. Of note, identifying the kinase(s), inhibition of which leads to toxicity, could allow redesign of dasatinib to no longer inhibit the kinase that is critical to the heart.\textsuperscript{41}

**Cardiomyopathy Associated With Small-Molecule Angiogenesis Inhibitors**

Although initially proposed by Dr Judah Folkman\textsuperscript{42} more than 40 years ago, inhibiting angiogenesis by targeting specific circulating proangiogenic factors or their receptors has become a major focus of cancer drug development in the past decade.\textsuperscript{43} Angiogenesis is mediated by the stabilization of the master transcription factor—hypoxia-inducible factor-α (HIFα)—leading to the transcription of a number of protumorigenic factors, including VEGF and platelet-derived growth factor. This system has been best described in clear cell renal cell carcinoma where sporadic mutations in the gene encoding for the von Hippel-Lindau protein play a causal role in tumorigenesis. von Hippel-Lindau protein is the substrate recognition component of an E3 ubiquitin ligase complex that targets HIFα for degradation with von Hippel-Lindau mutations leading to inappropriate stabilization (and hence activation) of HIF (specifically HIF2α) and induction of VEGF and other HIF targets.\textsuperscript{44} This model probably explains why renal cell carcinoma has been the main focus for FDA approval of angiogenesis inhibitors and why renal cell carcinoma remains the one cancer type where angiogenesis inhibitors are approved as single therapy and lead to modest benefit.\textsuperscript{45,46}

Bevacizumab (Avastin), the first FDA-approved drug in this class, is a monoclonal antibody targeting the soluble VEGF protein and is given intravenously. However, the newer FDA-approved drugs targeting angiogenesis (and the many currently in clinical trials) are given orally and target the tyrosine kinase receptors for VEGF, platelet-derived growth factor, and other factors. Examples include sunitinib (Sutent), sorafenib (Nexavar), and pazopanib (Votrient). Because VEGF inhibition is a central feature, the class of drugs is generally referred to as VEGF-signaling pathway (VSP) inhibitors; however, with respect to the tyrosine kinase inhibitors in this class, the term VSP inhibitor is a bit misleading given the drugs’ relative promiscuity. The latter serves as a double-edged sword, allowing the drugs to be approved for a wide range of cancers but also has implications for toxicity. For example, sunitinib targets several tyrosine kinase receptors, including all 3 VEGF receptors (VEGFR1, VEGFR2, VEGFR3), platelet-derived growth factor receptors α and β, tyrosine-protein kinase Kit, and fms-like tyrosine kinase 3, and has been approved for the treatment of gastrointestinal stromal tumor, advanced renal cell carcinoma, and advanced pancreatic neuroendocrine tumors. In this regard, it may be simplistic to generalize the cardiotoxicities in this section as a class effect because each drug has selective targets (Figure 2). VSP inhibitors represent arguably the fastest growing class of drugs for cancer therapy with the number of FDA-approved drugs nearly doubling in 2012 alone with many more drugs in this class currently awaiting FDA approval.\textsuperscript{6}

Clinical trials involving VSP inhibitors have not included routine screening for clinical HF or LV dysfunction. As a result, the emerging recognition of cardiomyopathy with VSP inhibitors is mostly based on retrospective analyses where there is potential for misclassification bias. A meta-analysis assessing 5 clinical trials (and involving 3784 patients with breast cancer) showed incidence of high-grade CHF to be 1.6% in patients treated with bevacizumab compared with 0.4% in the control or placebo groups, resulting in an overall relative risk of developing high-grade CHF of 4.74.\textsuperscript{40} Another meta-analysis assessing the propensity of patients receiving sunitinib to develop CHF (involving 6935 patients from 16 studies) suggested an overall incidence of all-grade and high-grade CHF of 4.1% and 1.5%, respectively; treatment with sunitinib was associated with an increased relative risk of developing all-grade and high-grade CHF (relative risk of 1.81 and 3.30, respectively).\textsuperscript{48} Single-institution studies suggest an incidence anywhere between 2.7% to 15% in patients on sunitinib having symptomatic CHF (and attributed to sunitinib).\textsuperscript{37-40}

Observational data from individual trials involving sunitinib suggest a higher incidence of asymptomatic cardiomyopathy. Among 75 patients with imatinib-resistant gastrointestinal stromal tumor in a phase II/III trial of sunitinib, 28% of patients had an absolute decrease in EF of at least 10%.\textsuperscript{8} An observational study of patients with metastatic renal cell carcinoma treated with sunitinib or sorafenib found that 33% of patients...
had a cardiac event, although cardiac event in this study ranged from an asymptomatic increase in cardiac enzymes to new LV dysfunction requiring intensive care.9

The above studies, however, probably underestimate the true incidence of cardiomyopathy in the setting of VSP inhibitor treatment for several reasons. First, as stated above, none of clinical trials involving VSP inhibitors prospectively monitored cardiac function, thus relying heavily on investigator judgment of clinical HF. Second, reporting of HF using National Cancer Institute’s Common Terminology Criteria of Adverse Events can be confusing given the various definitions for cardiomyopathy.50 Third, diagnosis of HF in cancer patients can be difficult given the often nonspecific symptoms that can arise with malignancy (such as fatigue or peripheral edema). Fourth, cardiomyopathy can present as asymptomatic LV dysfunction, thus underestimating the necessity of cardiac imaging in clinical trials. Fifth, long-term cardiac consequences of VSP inhibitors are completely unknown. Sixth, early clinical trials with novel cancer therapies usually exclude patients with a history of significant HF, uncontrolled hypertension, or other risk factors, whereas these exclusions do not always apply to the general population once a drug is FDA-approved. Finally, due to the relative promiscuity of novel VSP inhibitors, it is unclear if the early observations regarding the incidence and prognosis of cardiomyopathy associated with sunitinib extend to newer drugs in this class. In the future, prospective studies using close clinical and imaging follow-up of patients treated with VSP inhibitors are needed to get a better estimate of patients who develop LV dysfunction.6

There have been several proposed mechanisms for VSP inhibitor–associated HF. The most intriguing model that examines this is a mouse expressing a tunable transgene encoding a VEGF trap (in a sense recapitulating the effects of bevacizumab). In this model, the induction of the VEGF trap leads to decreased myocardial capillary density (capillary rarefaction), induction of hypoxia and hypoxia-inducible genes in the myocardium, and cardiac dysfunction, which is reversible on removal of the transgene.51 Similarly, mice in which platelet-derived growth factor receptor β is genetically deleted in the heart have decreased capillary density, increased myocardial hypoxia, and accentuated HF after transverse aortic constriction.52 These 2 studies suggest the intriguing possibility that induction of hypoxia and hypoxia-inducible genes in the heart (as may occur as a result of inhibition of angiogenesis in the heart after treatment with VSP inhibitors) may lead to cardiomyopathy. In keeping with this model, stabilization of HIFα in the heart is sufficient to induce reversible cardiomyopathy in mice.53,54 Although these preclinical models are intriguing, it remains to be seen whether myocardial hypoxia (as a result of capillary rarefaction) plays a causal role in cardiomyopathy associated with VSP inhibitors in humans. Nevertheless, these mouse models predict that VSP inhibitor–associated cardiomyopathy would lead to myocardial hibernation rather than myocardial death and that they would be reversible. Indeed, several studies suggest that sunitinib- and sorafenib-induced cardiomyopathy may be reversible.55 Moreover, sunitinib-induced cardiomyopathy in both mouse and humans show similar ultrastructural changes—including mitochondrial alterations—that are reversible after discontinuation of treatment56 (Figure 3).

Despite the increasing recognition of HF, hypertension is by far the most common cardiovascular toxicity associated with

![Figure 2. Angiogenesis inhibitors (vascular endothelial growth factor (VEGF) signaling pathway (VSP) inhibitors) being tested in human cancer trials.](http://circres.ahajournals.org/)

Although these agents are being referred to as VSP inhibitors, drugs such as sunitinib inhibit many other receptor tyrosine kinases, allowing them to be approved for the treatment of other cancers while, at the same time, creating the possibility for a wide range of off-target toxicities. FDA indicates Food and Drug Administration; HIF, hypoxia-inducible factor; PDGF, platelet-derived growth factor; PDGFR, PDGF receptor; TKI, tyrosine kinase inhibitor; and VEGFR, VEGF receptor. (Illustration Credit: Ben Smith.)
VSP with an incidence of hypertension of 19% to 25% with this class of agents.6,57 Newer VSP inhibitors such as axitinib and cediranib probably cause an even higher incidence of hypertension. For example, a recent trial with cediranib showed that 87% of the patients had hypertension.58 Blood pressure increase is rapid in most patients after initiation of treatment with VSP inhibitors and can be reversible once chemotherapy is stopped. There have been several proposed mechanisms for VSP inhibitor–associated hypertension. Both functional (inactivation of endothelial NO synthase and production of vasoconstrictors such as endothelin-1) and anatomic (capillary rarefaction) changes in the endothelium have been proposed as mechanisms of VSP inhibitor–associated hypertension.59 Interestingly, the resultant hypertension after initiation of VSP inhibitors is probably mediated via VEGF signaling and not due to an off-target effect. Consistent with this model, there is emerging evidence that elevations in blood pressure may predict superior tumor outcomes.59 Finally, interesting similarities exist between VSP inhibitor–associated hypertension and preeclampsia, a syndrome of hypertension and proteinuria affecting 5% of all pregnancies, which also probably results from dysregulation of VEGF signaling.6,59,60

In the absence of prospective studies detailing the extent of cardiomyopathy, we suggest a low threshold for assessing cardiac dysfunction after initiation with VSP inhibitors. Baseline echocardiogram to assess for structural heart disease should be considered, especially in patients with cardiac risk factors. Risk factors including hypertension should be aggressively treated during therapy and a repeat echocardiogram be done if the patient has symptoms concerning for HF. On detection of cardiomyopathy, VSP inhibitor treatment should be stopped and patients should be started on cardioprotective medications, including β-blockers and angiotensin-converting enzyme inhibitors. Given the potential reversibility of this class of cardiomyopathy,55 a repeat echocardiogram after stopping the VSP inhibitor is necessary. Less clear is whether the patient can be rechallenged with the same or another VSP inhibitor.

In addition, in all patients considered for VSP inhibitor treatment, blood pressure needs to be aggressively managed prior to initiation of chemotherapy and in keeping with JNC7 guidelines. Because VSP inhibitors have been associated with proteinuria, testing for urine proteins should be performed before and after initiation of treatment, and select patients should be referred to a nephrologist. We advocate

![Ultrastructural evidence of mitochondrial injury in mice treated with the vascular endothelial growth factor signaling pathway (VSP) inhibitor sunitinib (A), and significant reversibility of that injury in a patient after withdrawal of sunitinib (B).](http://circres.ahajournals.org/)

**Figure 3.** Ultrastructural evidence of mitochondrial injury in mice treated with the vascular endothelial growth factor signaling pathway (VSP) inhibitor sunitinib (A), and significant reversibility of that injury in a patient after withdrawal of sunitinib (B). **A.** Mice were treated with doses of sunitinib that would mimic levels in humans. Note the mitochondrial injury on transmission electron microscopy (EM) (right). **B.** Left, Transmission EM images from a patient who developed profound heart failure while receiving sunitinib. Note the marked mitochondrial injury. Right, Repeat biopsy showing marked resolution of injury 1 month after discontinuation of sunitinib and addition of standard heart failure treatment. Reprinted with permission from Chu et al.8 Authorization for this adaptation has been obtained both from the owner of the copyright in the original work and from the owner of copyright in the translation or adaptation.
Understanding Her2 Inhibitors and Agonists

Trastuzumab

More than 20% of breast carcinomas overexpress HER2/neu (also known as epidermal growth factor receptor-B2 or ErbB2 in the mouse). Trastuzumab (Herceptin) is a humanized monoclonal antibody that targets the extracellular domain of the Her2 receptor and is used widely to treat HER2+ breast cancer. Currently one of the few approved therapies for patients with early-stage and metastatic HER2+ disease, this agent has dramatically altered the landscape of breast cancer therapy.60

Trastuzumab binds to the β-hairpin region of domain II of the HER2 receptor in tumor cells. There are multiple proposed mechanisms of trastuzumab’s actions.61 These include the following: (1) antibody-dependent cellular cytotoxicity, (2) inhibition of ErbB2 extracellular domain cleavage and the expression of the constitutively active fragment, (3) inhibition of ligand-independent ErbB2 receptor heterodimerization, (4) inhibition of angiogenesis, (5) induction of cell cycle arrest, and (6) interference with DNA repair. The ability of trastuzumab to inhibit the formation of the ErbB2–ErbB3 complex in cancer cells and downstream activation of the PI3K/Akt pathway is thought to be a particularly potent mechanism of action of this agent.

Although trastuzumab has demonstrated remarkable efficacy in the treatment of HER2-positive breast cancer, there is a clinically significant incidence of cardiotoxicity. A portion of patients experience an important but primarily reversible cardiotoxic effect, manifest as a decline in LVEF.64 Experience from large clinical trials demonstrate an ≈9.8% incidence of LV dysfunction and 2.7% incidence of severe, symptomatic HF.65 However, when used in combination with anthracyclines, the incidence of cardiac dysfunction increases to 16% to 20%, with a 7-fold increased risk of HF or cardiomyopathy.2 Although clinical experience suggests that recovery of LVEF occurs in the majority of patients within the first year after exposure, either with temporary cessation of trastuzumab or in combination with standard HF therapy, not all patients experience recovery of cardiac function.2

In addition to prior anthracycline exposure, there are a number of clinical risk factors for cardiotoxicity, including hypertension,1 suggesting that the risk of cardiotoxicity with trastuzumab increases with additional cardiac stress, potentially indicative of a 2-hit model of trastuzumab-induced cardiotoxicity, in which trastuzumab somehow interferes with the cardiac stress response.66 However, the pathogenesis of trastuzumab-induced cardiotoxicity is still unclear and remains an area of active investigation.

One central hypothesis for the pathophysiology of trastuzumab cardiotoxicity is related to alterations in the NRG and ErbB pathway, which is established as a critical pathway in fetal heart development and the maintenance of adult cardiac function.67,68 NRG1 is a signaling protein released from microvascular endothelial cells that acts in a paracrine and juxtacrine fashion to activate the ErbB family of tyrosine kinase receptors expressed in cardiac myocytes.69 In adult cardiomyocytes, NRG1 binds the ErbB4 receptor, resulting in ErbB4/ErbB4 homodimerization or ErbB4/ErbB2 heterodimerization. In response, the PI3-K/Akt, mitogen-activated protein kinase/extracellular signal-regulated kinase pathways, as well as Src/focal adhesion kinase and NO synthase are activated and regulate cardiac stress responses.69,70 Recent data also demonstrate that stimulation of the NRG1/ErbB4 signaling pathway induces cell cycle reentry of differentiated cardiomyocytes, cardiomyocyte proliferation, and promotion of cardiac repair.13 Furthermore, in vitro and in vivo models support a cardioprotective role for endogenous, endothelial cell–derived NRG and ErbB4 in response to hypoxic/ischemic injury.71

The NRG1/ErbB ligand–dependent signaling pathway is thought to be crucial in the adaptive response to cardiac stress, as NRG1/ErbB-deficient animals develop a dilated cardiomyopathy phenotype, increased susceptibility to cardiac injury and to anthracycline exposure, and decreased survival.3,72 Basic science evidence and early translational studies in both animals and humans suggest that augmentation of the NRG/ErbB signaling pathway through exogenous delivery is beneficial and results in substantial improvements in cardiac function and survival in cardiomyopathy models.14,73

Although it is tempting to speculate that trastuzumab-related cardiac damage may be, at least in part, related to the inhibition of the NRG1/ErbB4/ErbB2 pathway in cardiomyocytes, the precise mechanisms are unknown, and direct causal relationships and downstream mediators have not been defined.74 We hypothesize that NRG/ErbB inhibition has important effects on cardiomyocyte growth, angiogenesis, and maintenance of myofibrillar structure through PI3-K/Akt and mitogen-activated protein kinase/extracellular signal-regulated kinase signaling, and suggest these areas should be a continued focus of further study. Similarly, the potential relevance of associated ligands such as heparin-binding epidermal growth factor and receptors such as ErbB3, both of which may have a role in the cardiovascular system, remain to be elucidated in trastuzumab cardiotoxicity.75,76

An improved mechanistic understanding could be translated into strategies to improve risk stratification and develop new therapies for cardiac repair. Several groups have been actively studying the role of circulating factors reflective of the NRG/ErbB signaling pathway in identifying patients at risk for adverse cardiovascular outcomes in HF and with exposure to doxorubicin and trastuzumab. In studies done in 899 patients with chronic HF, serum NRG1b was significantly elevated in patients with New York Heart Association class IV HF with a median value of 6.2 ng/mL versus 4.4 ng/mL for class I HF patients.
(P=0.002). There was also an increased risk of death or cardiac transplantation during a median follow-up of 2.4 years (adjusted hazard ratio 1.58 [95% confidence interval, 1.04–2.39; P=0.03] comparing 4th versus 1st NRG1β quartile). Similarly, a small case–control study of chronic HF patients found increased levels of circulating ErbB2 in the serum of HF patients (n=50) versus age- and sex-matched controls (n=15), possibly indicative of increased shedding of ErbB2 into the circulation in HF.78

In breast cancer patients undergoing chemotherapy, initial observations suggest that exposure to anthracyclines result in a significant reduction in circulating NRG1β levels. This was postulated to be indicative of endothelial dysfunction and, potentially, downregulation or dysfunction of this pathway. Other groups have corroborated these findings in independent cohorts and also suggested there may be correlations between NRG1β levels and changes in LVEF.79 More precise phenotyping of the time course of NRG1 expression during exposure to cancer therapy and how this may relate to subsequent cardiotoxicity are topics of active investigation, as the potential adaptive activation and maladaptive depression of NRG/ErbB signaling may be relevant to trastuzumab as well as doxorubicin cardiotoxicity. This additional work will also clarify the role of NRG1 as a biomarker for risk prediction in cancer therapy–induced cardiotoxicity.

**Novel Her2 Therapies for Breast Cancer**

The success of trastuzumab in the treatment of both early and metastatic breast cancer has led to the development of a number of other agents targeting the Her2 receptor. Although early studies suggest that these novel agents may be less cardiotoxic than trastuzumab, the complexity here is underscored by the fact that these novel agents are being tested in combination with, rather than as an alternate to, trastuzumab (see Figure 4).

**Lapatinib**

Lapatinib is a small-molecule dual tyrosine kinase inhibitor of EGFR1 and ErbB2 that competes with ATP for binding to the ATP pocket of the kinase. If ATP cannot access the pocket, downstream targets of EGFR and ErbB2 cannot be phosphorylated and thus cannot be activated. Consequently, downstream targets that promote cancer growth and/or angiogenesis will be blocked.80 Lapatinib is thought to enhance trastuzumab’s effects in a synergistic fashion, and as such, dual targeting of HER2-positive tumors with trastuzumab and lapatinib is being used given the primary and acquired resistance of these agents when used as monotherapy.81 Although trastuzumab inhibits ligand-independent ErbB2 and ErbB3 dimerization and acts via antibody-dependent cellular cytotoxicity, lapatinib blocks ligand-dependent heterodimer signaling and prevents signaling of the truncated version of the HER2 receptor. Therefore, lapatinib may also enhance trastuzumab-dependent antibody-dependent cellular cytotoxicity through the accumulation of HER2 at the cell surface.86

In recent phase II and III clinical trials, the rates of cardiotoxicity with lapatinib have been reported to be low, on the order of 1.5% to 2.2%.82 Nevertheless, the generalizability and interpretation of such early studies with lapatinib, with respect to cardiotoxicity, is limited given patient enrollment is restricted to those without cardiovascular disease and the various definitions used to define cardiotoxicity. Interestingly, in many of these published studies comparing lapatinib and trastuzumab, the rates of cardiotoxicity observed with trastuzumab alone have also been less than that reported in retrospective analyses of nonclinical trial populations.83 The true incidence of cardiotoxicity will likely be revealed with continued experience with these agents.

Interestingly, recent in vitro data suggest that EGFR/ErbB2 inhibition may result in a different cardiac safety profile as compared with trastuzumab. In human cardiomyocytes, administration...
of GW2974, an equipotent inhibitor of EGFR/ErbB2, resulted in increased levels of activated adenosine monophosphate-activated protein kinase in a calcium-dependent, Akt-independent fashion. AMPK, a well-known master regulator of metabolic processes particularly in the setting of stress, was critical in maintaining human cardiomyocyte survival and resulted in reduced cellular lipid content, increased fatty acid oxidation, and increased production of ATP. In contrast, there was no evidence for AMPK activation in trastuzumab-treated human cardiomyocytes.

However, other studies show, like trastuzumab, EGFR/ErbB2 inhibition via intracellular tyrosine kinase inhibition is associated with myofibrillar disarray in adult rat ventricular cardiomyocytes, with worse damage observed in combination with doxorubicin. Furthermore, inhibition of EGFR/ErbB2 also inhibits phosphorylation of Erk1/2, which may also be important in modulating trastuzumab cardiotoxicity.

**Pertuzumab**

Pertuzumab is a recombinant humanized monoclonal antibody that targets an epitope near the center of the extracellular domain II of ErbB2 and sterically inhibits ErbB2 homo- and heterodimerization. Inhibition of ErbB2 dimerization by pertuzumab has been shown to block subsequent activation of Akt and Erk1/2.

Clinical experience with pertuzumab is growing, and rates of cardiotoxicity have not yet fully been established. In phase II studies of pertuzumab use as monotherapy in patients with Her2-negative breast cancer with prior exposure to anthracycline-containing chemotherapy, 10% of patients experienced a decline in LVEF of ≥10% to <50% that occurred at a median timeframe of 100 days. All patients who experienced cardiotoxicity had borderline normal LVEF, and again there was a reversible component. Similar findings were observed in additional cohorts, where cardiac events typically occurred in patients with a prior cardiovascular disease history. Finally, a pivotal study combining pertuzumab, trastuzumab, and docetaxel showed similar rates of cardiac dysfunction, as placebo, trastuzumab, and docetaxel, for first-line treatment of HER2-positive metastatic breast cancer, who had previously been treated with a taxane and trastuzumab, to T-DM1 or lapatinib and capecitabine. Here, 8 of 481 patients treated had an LVEF of <50% that was ≥15% below baseline (and comparable to the lapatinib and capecitabine group). Three of the 481 had an LVEF decline to <40%. Although in this study the incidence of cardiotoxicity appears to be low, additional experience is necessary before establishing any conclusions.

**What Can Cardio-Oncology Teach Us About HF?**

Understanding the mechanisms behind the cardiomyopathies that arise as a result of targeted cancer therapies and developing strategies to treat these complications are important for the cardiovascular care of the cancer patient. Understanding these cardiomyopathies may also have implications for more common types of HF and may provide unexpected insights into the biology of the heart. For example, the understanding that HER2 signaling plays a critical role in cardiovascular homeostasis has possible implications for prognosis and treatment for more common forms of HF. As described above, circulating levels of NRG1 (the agonist for HER2 in the heart) correlate with disease severity and the risk of death. In addition, recombinant NRG1 is now under investigation as a therapeutic molecule in severe HF. Likewise, emerging data during the past year suggest that VSP inhibitor–associated cardiomyopathy may have implications for peripartum cardiomyopathy, where impaired VEGF signaling probably plays a causal role. In this regard, with the explosion of novel cancer therapeutics being tested in clinical trials, we may just be observing the tip of the iceberg. For example, both mammalian target of rapamycin inhibitors and PI3K inhibitors are being tested in breast cancer trials (and often in combination with anthracyclines and HER2-targeted therapies). Although there remains a dearth of data with respect to the possible cardiovascular sequelae of these agents, biologically plausible mechanisms suggest adverse cardiovascular and metabolic consequences.

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