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DOI:

[10.2147/BCTT.S54414](https://doi.org/10.2147/BCTT.S54414)

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Document Version

Publisher's PDF, also known as Version of record

Citation for published version (Harvard):

Feldinger, K & Kong, A 2015, 'Profile of neratinib and its potential in the treatment of breast cancer', *Breast Cancer*, vol. 2015, no. 7, pp. 147-162. <https://doi.org/10.2147/BCTT.S54414>

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Profile of neratinib and its potential in the treatment of breast cancer

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Abstract: The HER (ErbB) receptor tyrosine kinase receptors are implicated in many cancers and several anti-HER treatments are now approved. In recent years, a new group of compounds that bind irreversibly to the adenosine triphosphate binding pocket of HER receptors have been developed. One of these compounds, neratinib, has passed preclinical phases and is currently undergoing various clinical trials. This manuscript reviews the preclinical as well as clinical data on neratinib. As a pan-HER inhibitor, this irreversible tyrosine kinase inhibitor binds and inhibits the tyrosine kinase activity of epidermal growth factor receptors, EGFR (or HER1), HER2 and HER4, which leads to reduced phosphorylation and activation of downstream signaling pathways. Neratinib has been shown to be effective against HER2-overexpressing or mutant tumors in vitro and in vivo. Neratinib is currently being investigated in various clinical trials in breast cancers and other solid tumors, including those with HER2 mutation. Earlier studies have already shown promising clinical activity for neratinib. However, more translational research is required to investigate biomarkers that could help to predict response and resistance for selection of appropriate patients for treatment with neratinib, either as monotherapy or in combination with other drug(s).

Keywords: neratinib, HKI 272, pan-HER inhibitor, irreversible tyrosine kinase inhibitor, HER (ErbB), breast cancer

Introduction

The family of HER (ErbB) receptor tyrosine kinases consists of four members, ie, epidermal growth factor receptors [EGFR (HER1 or ErbB1), HER2 (ErbB2, neu), HER3 (ErbB3), and HER4 (ErbB4)].¹ Overexpression, mutation, or aberrant activity of these receptors has been implicated in various types of cancer. HER2 is overexpressed in approximately 15%–20% of all breast cancers¹ and is correlated with poor prognosis.² HER receptors comprise an extracellular domain, a single transmembrane domain, and an intracellular tyrosine kinase domain.³ A disintegrin and metalloproteinases (ADAMs) shed the ligands that are needed for HER member activation. Eleven ligands are known to bind to the different receptors of the family, as shown in Figure 1;³ however, HER2 does not have a known ligand.⁴ Ligand binding induces a conformational change in HER receptors 1, 3, and 4, which exposes the dimerization domain. This facilitates homodimerization or heterodimerization and transphosphorylation of the tyrosine kinase domains.⁵ Subsequently, downstream signaling pathways, most prominently the phosphatidylinositol 3-kinase and mitogen-activated protein kinase pathways, are activated and promote survival and proliferation.^{6–8} HER2 adopts a constant “open” conformation, with the dimerization domain being always available.⁹ It was shown to be the preferred dimerization partner within the HER receptor network and it can also form potent homodimers.¹⁰

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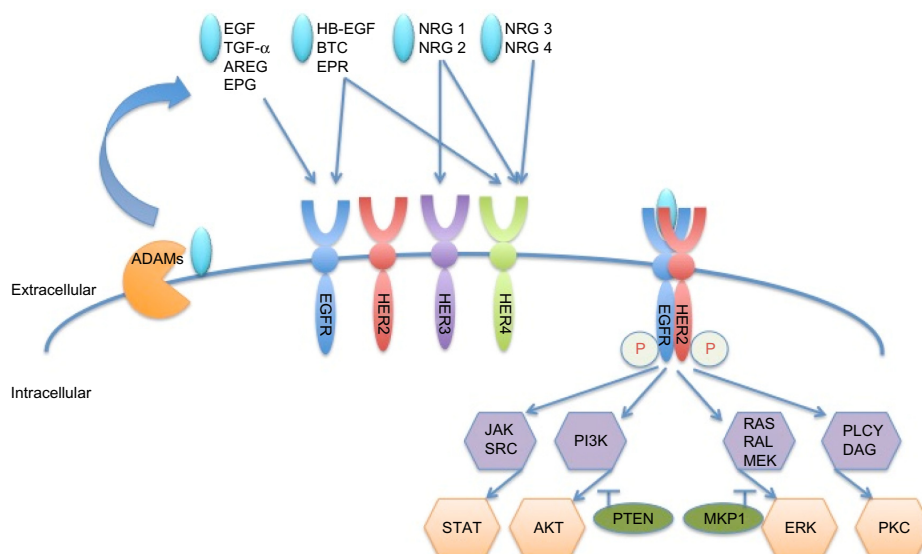


Figure 1 HER member family and activation.

Abbreviations: ADAMs, A disintegrin and metalloproteinases; EGF, epidermal growth factor; TGF, tumor growth factor; AREG, amphiregulin; EPG, epigen; HB-EGF, heparin-binding EGF-like growth factor; BTC, betacellulin; EPR, epiregulin; NRG, neuregulin; PI3K, phosphatidylinoside 3-kinase; PTEN, phosphatase and tensin homolog; PKC, protein kinase C; STAT, signal transducer and activator of transcription; JAK, Janus kinase.

Development of neratinib to target HER family kinase activity

Neratinib (HKI-272, Puma Biotechnology Inc., Los Angeles, CA, USA) is an oral tyrosine kinase inhibitor (TKI). The scientific approach behind the development of this and other similar compounds was to design small molecules that could bind to the tyrosine kinase domain and inhibit its interaction with adenosine triphosphate (ATP) in order to prevent receptor phosphorylation. A selection of compounds with relevant

references is listed in Figure 2 and Table 1, although a direct comparison of IC_{50} values is difficult due to different assay conditions. Earlier compounds such as erlotinib (Tarceva[®]) and gefitinib (Iressa[®]), which are approved in non-small cell lung cancer (NSCLC), or lapatinib (Tyverb[®]), which is licensed for HER2-positive breast cancer, were designed as reversible compounds that directly compete with ATP for binding. However, considering the high endogenous ATP levels within the cell (mM range) and that drug resistance

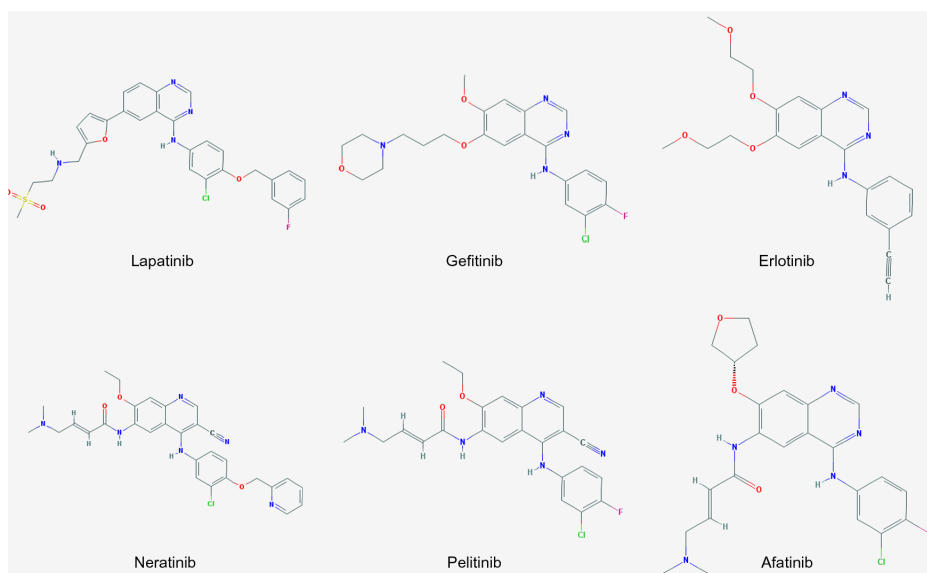


Figure 2 Chemical structure of tyrosine kinase inhibitors.

Note: Adapted Data from PubChem.¹⁶⁻²¹

Table 1 Comparison of various tyrosine kinase inhibitors

Compound	Binding	IC ₅₀ (nM)		
		EGFR	HER2	HER4
Gefitinib	Reversible	27–33 ^{12,*} 0.4–4.7 ^{13,**}	≥3,700 ^{12,*} 416–1,830 ^{13,**}	293–323 ^{13,**}
Erlotinib	Reversible	2 ^{12,*} 0.9–1.7 ^{13,**}	>1,000 ^{12,*} 238–698 ^{13,**}	579–756 ^{13,**}
Lapatinib	Reversible	11 ^{12,*} 0.3–17	9 ^{12,*} 6–25	367 ^{12,*} 18–30
Neratinib	Irreversible	92 ^{14,***}	59 ^{14,***}	
Afatinib	Irreversible	0.2–0.7 ^{13,**}	7–25 ^{13,**}	0.7–1.7 ^{13,**}
Canertinib	Irreversible	0.8 ^{12,*} 0.3–1.7 ^{13,**}	19 ^{12,*} 22–72 ^{13,**}	7 ^{12,*} 0.8–10 ^{13,**}
Dacomitinib	Irreversible	6 ^{15,#}	46 ^{15,#}	74 ^{15,#}

Notes: Measuring IC₅₀ values is highly dependent on the assay set-up; please refer to individual references for more information on exact methods. *Purified enzyme kinases were used to calculate in vitro IC₅₀ values (please refer to review); **purified cytoplasmic tyrosine kinase domains were used in in vitro kinase assays (non-radioactive for EGFR and HER2 and radioactive for HER4); ***purified cytoplasmic domains were used to measure autophosphorylation using a time-resolved fluorometry assay; #purified catalytic domains were used in in vitro enzyme-linked immunosorbent-based kinase assays.

Abbreviations: EGFR, epidermal growth factor receptor; TKR, tyrosine kinase receptor.

is a common problem with these reversible inhibitors, there was a need to develop a more potent inhibitor that could have enhanced and sustained antitumor activity.¹¹

A variety of irreversible inhibitors of quinazoline derivatives has been developed, including dacomitinib and afatinib, which showed a high affinity and efficacy in inhibiting autophosphorylation of EGFR.²² Neratinib is a compound comprising a quinolone core with the same reactive substituent as afatinib, but with a lower affinity and biochemical potency.²² The effectiveness of these compounds is based on a Michael acceptor moiety, which is designed to form a covalent bond with the conserved cysteine residue at the lip of the EGFR ATP binding site.^{23–25} Neratinib interacts with cysteine residues Cys-773 and Cys-805 in EGFR and HER2, respectively, in the ATP binding pocket.¹¹ Due to this selective binding, a higher specificity of the compound is achieved. It was shown that neratinib did not significantly inhibit serine-threonine kinases such as AKT in cell-free assays. Tyrosine kinases tested included c-met, Kdr (vascular endothelial growth factor receptor 2), and Src, and either no effect or a 14-fold and 24-fold decreased efficacy, respectively, was found in comparison with HER2.¹⁴

Neratinib was developed as a modification of EKB-569 (pelitinib), an irreversible EGFR inhibitor developed by Wyeth Pharmaceuticals.¹¹ The chemical name is 2-butenamide, N-[4- [[3-chloro-4-(2-pyridinylmethoxy) phenyl] amino]-3-cyano-7-ethoxy-6-quinolinyl]-4-(dimethylamino)-, (2E)-, (2Z) -2-butenedioate (1:1). In comparison with EKB-569, neratinib has a lipophilic 2-pyridinylmethyl moiety at

the para-position of the aniline and a lipophilic chlorine atom at the meta-position, which is thought to improve its activity against HER2.^{14,24} However, as the cysteine residue required for binding is conserved in three of the HER receptors, ie, EGFR, HER2, and HER4, neratinib is a pan-HER inhibitor.¹¹ Neratinib inhibits EGFR and HER2 at IC₅₀ values of 92 nM and 59 nM, respectively; specific IC₅₀ data for HER4 has not been published.¹⁴ However, the compound is similar to afatinib, so activity against HER4 can be expected and has indeed been shown previously.^{26,27}

Efficacy of neratinib in preclinical models

As neratinib binds irreversibly to the ATP binding pocket of HER member receptor tyrosine kinases, it was hypothesized that after binding a prolonged bioavailability in the blood would not be needed. Therefore, the efficacy of the compound would only depend on receptor turnover.¹¹ Acute treatment with low doses of neratinib led to a decrease of HER2 and EGFR phosphorylation in HER2-overexpressing BT474 and EGFR-amplified A431 cells, respectively, which persisted even after the removal of the drug. However, the time point chosen was only 5 hours.¹⁴ Neratinib was shown to decrease tumor growth in EGFR and HER2-expressing cell lines in vitro, which was correlated with a decrease in cyclin D1 and an increased level of p27, leading to G1-S cell cycle arrest and an increased sub-G1 population, indicating apoptosis.¹⁴

HER2-positive breast cancer

Despite reasonable IC₅₀ values with regard to both EGFR and HER2, several studies have shown that neratinib is more effective in HER2-positive breast cancers relative to other breast cancer subtypes. In a study using a panel of cell lines, we showed that the response to neratinib was correlated with baseline HER2 and phosphorylated HER2 levels, but not with EGFR levels in vitro.²⁶ Interestingly, neratinib decreased the activation of phosphatidylinositol 3-kinase and mitogen-activated protein kinase downstream pathways, and the activity against AKT and ERK could be correlated with efficacy.^{14,26,28} Other biomarker candidates that have been investigated in vitro include upregulation of RB1CC1, HER3, FOXO3a, and NR3C1 as well as downregulation of CCND1 mRNA, all of which have been correlated with response to neratinib.²⁹ In vivo, neratinib was shown to be more effective in decreasing xenograft tumor growth of EGFR-amplified (A431) and HER2-overexpressing (BT474 and SKOV3) cell lines compared with low EGFR and HER2-expressing cell lines (MCF-7 and MX-1) in athymic (nude) mice.¹⁴ However,

the decrease in tumor growth in the EGFR-dependent tumor model was less than that seen in HER-2-dependent tumors at comparable doses.¹⁴

Dual targeting of HER2-positive breast cancers and overcoming treatment resistance

Considerable effort has been made to target HER2 signaling. The first treatment approved by the US Food and Drug Administration was the monoclonal antibody trastuzumab (Herceptin®), which targets domain IV of the extracellular domain of HER2.⁹ Trastuzumab was approved in 1998 and has been shown to be effective, particularly in combination with chemotherapeutic agents, in the treatment of various stages of HER2-positive breast cancer.^{30–33} However, *de novo* or acquired resistance to trastuzumab is frequent and is still a subject of extensive research.

Previous reports identified phosphatase and tensin homolog (PTEN) deficiency,^{34,35} phosphatidylinositol 3-kinase (PI3K) mutation,³⁶ loss of p27,³⁷ and reduced binding of the antibody due to HER2 cleavage³⁸ or allosteric hindrance^{39,40} as mechanisms involved in trastuzumab resistance. Interestingly, it was also reported that treatment with trastuzumab led to an increased activation of other receptor tyrosine kinases, including the insulin-like growth factor 1 receptor (IGFR1)³⁸ and c-Met.⁴¹ In addition, we have previously shown that trastuzumab induced an increase of ADAM10 and ADAM17 expression, which enhanced the release of the HER ligands betacellulin and heregulin (neuregulin), resulting in activation of HER receptors as well as downstream signaling pathways during prolonged treatment with trastuzumab.^{42,43}

A ligand-dependent mechanism has also been reported *in vitro* with regard to lapatinib resistance.^{44,45}

As shown in Figure 3, neratinib targets tyrosine kinase activity at the intracellular domain of the HER receptors (EGFR, HER2, and HER4), whereas trastuzumab targets the extracellular domain of HER2. This difference in mechanism of action would explain the improved response when both drugs are combined, since trastuzumab can induce ligand-dependent activation of HER receptors,^{42,43} whereas neratinib inhibits the phosphorylation and activity of HER receptors. Indeed, it has been shown that neratinib can overcome trastuzumab resistance *in vitro*.²⁶ It was reported that neratinib was able to suppress ligand-stimulated HER2–HER3 dimers and could effectively disrupt preformed HER2–HER3 dimers in non-HER2-overexpressing MCF7 cells more effectively than lapatinib.⁴⁶ Additionally, both TKIs decreased internalization of the HER2 receptor from the cell membrane, leading to increased trastuzumab-induced antibody-dependent cellular cytotoxicity.⁴⁶ It has been shown that during trastuzumab treatment and resistance, HER4 cleavage and its translocation to the nucleus was increased; and nuclear HER4 was associated with a poor prognosis.²⁷ However, cotreatment with neratinib decreased trastuzumab-induced nuclear HER4 *in vitro* and in BT474 xenograft models.²⁷ In the same *in vivo* model, it was shown that trastuzumab and neratinib treatment in combination was more effective than either treatment alone.²⁶

Additionally, neratinib was also shown to enhance response when added to mammalian target of rapamycin/phosphatidylinositol 3-kinase inhibitors⁴⁷ and the PARP inhibitor olaparib.⁴⁸ These results, as well as those of the study from Seyhan et al²⁸ point to the potential added benefit

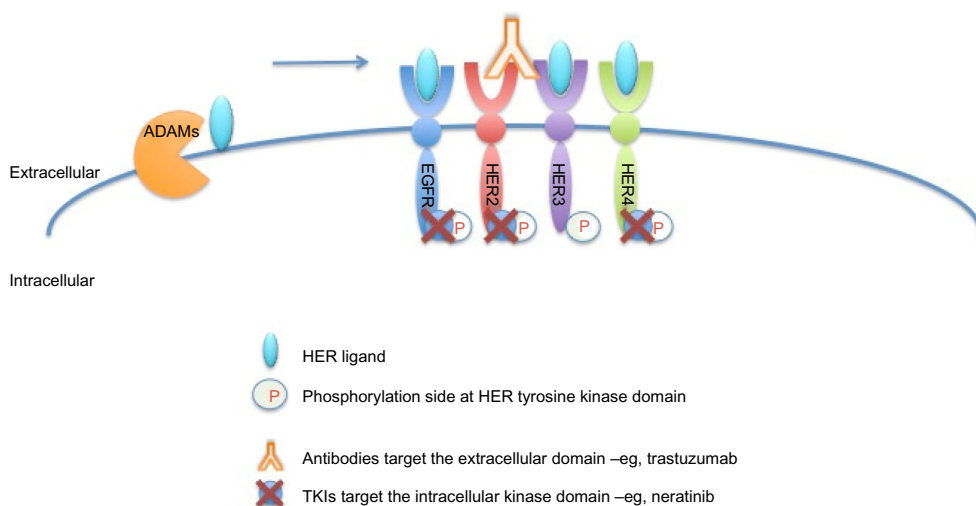


Figure 3 Sites of interaction of trastuzumab and neratinib with HER receptors.

Abbreviations: ADAMs, A disintegrin and metalloproteinases; TKIs, tyrosine kinase inhibitors; EGFR, epidermal growth factor receptor.

of using neratinib as a combinational treatment option alongside other targeted treatments as well as conventional chemotherapeutics.

We have recently shown that neuregulin (NRG1) can counteract the response to lapatinib, which was improved by the combination of lapatinib with pertuzumab, an antibody binding to the HER2 dimerization domain.⁴⁵ It would thus be interesting to test whether NRG1 mediates resistance to neratinib and whether pertuzumab could also enhance the response to neratinib. In addition, since the combination of trastuzumab with new agent(s), including a heat shock protein 90 inhibitor,⁴⁹ was shown to be additional or synergistic, it will be interesting to test the combination of neratinib with these new agents. However, more data will be needed to guide the sequence and/or combinations of different compounds, which could benefit patients.

Neratinib for CNS metastasis in HER2-positive breast cancer

A major problem in the treatment of patients with HER2-positive breast cancer is the high incidence of central nervous system (CNS) metastases. Although clinical studies suggest that patients with CNS metastases who receive trastuzumab have an increased overall survival compared with patients who do not, it is well understood that penetration of trastuzumab across the blood–brain barrier is inefficient.⁵⁰ Therefore, there is a growing interest in using TKIs to target CNS disease in patients with HER2-positive breast cancer. One obvious advantage of these small-molecule compounds is their size. The blood–brain barrier is at least in part regulated by ATP-binding cassette (ABC) transporters, which contribute to multidrug resistance by actively extruding the drug compounds. Recent studies have shown that lapatinib is a substrate as well as an inhibitor of ABCB1, potentially explaining why brain concentrations of lapatinib tend to be lower.⁵¹ However, in contrast with lapatinib, neratinib has been shown to reverse ABCB1-mediated chemoresistance⁵² and it is unaltered by the presence of the ABCG2 transporter.⁵³ Moreover, neratinib could inhibit the function of this transporter at higher doses, leading to an increased level of ABCG2 substrate drugs within cells.⁵³ At the 2014 American Society of Clinical Oncology annual meeting, the preliminary data from a clinical trial investigating the efficacy of neratinib in HER2-positive breast cancer patients presenting with brain metastasis ([ClinicalTrials.gov](https://clinicaltrials.gov/ct2/show/study/NCT01494662) identifier NCT01494662, see Table 2) suggested that neratinib could help to control disease in some HER2-positive breast cancer patients presenting with brain metastasis; however, the CNS overall response rate was only 7.5%.⁵⁴

HER2-negative breast cancer

There is an interest in assessing whether neratinib could also be effective in breast tumors with lower HER2 expression, eg, immunohistochemistry (IHC) 2+ but fluorescence in situ hybridization (FISH)-negative patients. These will be those tumors that do not fulfill the current criteria for HER2-positive breast cancer. HER2 testing and its criteria have not always been consistent. Initially, the US Food and Drug Administration guidelines for HER2 testing recommended that if $\geq 10\%$ of the tumor cells show strong (3+) staining by IHC or if the HER2/chromosome 17 ratio at FISH is ≥ 2.0 , the tumor is classified as HER2-positive.⁵⁵ The threshold recommendations were updated by the American Society of Clinical Oncology/College of American Pathologists to $\geq 30\%$ of tumor cells with 3+ staining and a ratio of ≥ 2.2 for IHC and FISH, respectively, in 2007.⁵⁶ However, the latest recommendation states thresholds similar to the initial guidelines.⁵⁷ To be eligible for HER2 targeting treatments, breast cancer patients have to be classified as HER2-positive, depending on the local criteria used. However, IHC and FISH testing can be equivocal, and in two trials, patients initially classified as HER2-positive were found to be HER2-negative upon retesting. However, some of these negative patients still responded to treatment with trastuzumab.^{58,59}

As the original HER2 positivity threshold was based on trastuzumab response, it is unknown whether the threshold should be different for TKIs such as lapatinib and neratinib, since there have been studies suggesting that breast cancer with a lower HER2 level may benefit from TKIs. For example, one study showed that patients with low HER2 by IHC may be more sensitive to lapatinib than to trastuzumab.⁶⁰ The I-SPY2 trial suggested that HER2-negative patients may benefit from the addition of neratinib to chemotherapy (see below).⁶¹

Triple-negative breast cancer

Triple negative breast cancer (TNBC) represents a group of heterogeneous breast cancers that lack expression of the estrogen receptor and progesterone receptor as well as HER2 overexpression or gene amplification. Patients with TNBC tend to have a poor prognosis and very aggressive breast cancer with a lack of targeted therapy options. EGFR is frequently overexpressed in TNBC, and thus there is an interest in targeting this subtype of cancer using EGFR inhibitors.⁶² It was reported that ADAM17 was expressed at significantly higher levels in TNBC than in non-TNBC, and an ADAM17 inhibitor could inhibit cell proliferation by a decrease of the release of the EGFR ligands and could also

Table 2 Clinical trials involving neratinib in breast cancer

NCT identifier	Title	Study participants	Study design	Patients (n)	Objectives	Status	Reference
NCT01423123	Combination of weekly paclitaxel with neratinib and trastuzumab in women with metastatic HER2-positive breast cancer	Women \geq 18 years with metastatic HER2-positive BC	Open-label, non-randomized, single arm, Phase I	21	Safety/tolerability of neratinib + trastuzumab + paclitaxel	Completed	82
NCT00708903	Study to examine the effect of HKI-272 on rhythms of the heart (cardiac repolarization)	Healthy participants aged 18–50 years	Double-blind, randomized, Phase I	60	Pharmacokinetic/dynamic comparison of neratinib vs placebo vs moxifloxacin	Completed	85
NCT00146172	Study evaluating HKI-272 in tumors	Patients aged \geq 18 years with HER2/EGFR-overexpressing tumors	Open-label, non-randomized, Phase I	72	Safety (see title)	Completed	78
NCT00398567	Phase I/II study of HKI-272 (neratinib) in combination with trastuzumab (Herceptin [®]) in subjects with advanced breast cancer	Patients aged \geq 18 years with advanced HER2-positive BC that is not curable by available therapy and who progressed following at least one trastuzumab-containing cytotoxic chemotherapy regimen	Open-label, non-randomized, Phase I/II	45	Safety/efficacy (see title)	Ongoing, not recruiting	
NCT00445458	Phase I/II study of HKI-272 (neratinib) in combination with paclitaxel (Taxol [®]) in subjects with solid tumors and breast cancer	Patients aged \geq 18 years with a pathologically confirmed solid tumor not curable with available standard therapy (Part I) or HER2-positive pathologically confirmed BC with prior trastuzumab treatment	Open-label, randomized, Phase I/II	115	Safety/efficacy (see title)	Ongoing, not recruiting	81
NCT00777101	Study evaluating neratinib vs lapatinib + capecitabine for ErbB2-positive advanced breast cancer	Women aged \geq 18 years with locally advanced or metastatic HER2-positive BC with prior trastuzumab + taxane	Open-label, randomized, Phase II	233	Safety/efficacy (see title)	Ongoing, not recruiting	86
NCT02236000	A dose-escalation study evaluating the combination of trastuzumab emtansine (T-DM1) with neratinib in women with metastatic HER2-positive breast cancer	Women aged \geq 18 years with metastatic HER2-positive BC with one (and only one) prior regimen of anti-HER2-based therapy for metastatic disease	Open-label, single arm, Phase I/II	63	Safety/efficacy (see title)	Ongoing, not recruiting	
NCT00878709 ExteNET	Study evaluating the effects of neratinib after adjuvant trastuzumab in women with early stage breast cancer	Women aged \geq 18 years with confirmed HER2-positive BC with prior trastuzumab	Double-blind, randomized, Phase III	2,821	Efficacy (see title)	Ongoing, not recruiting	
NCT00741260	Study evaluating the combination of neratinib and capecitabine in solid tumors and breast cancer	Women aged \geq 18 years with confirmed pathologic diagnosis of a solid tumor not curable with available therapies for which neratinib + capecitabine is a reasonable treatment option (Part I) and with HER2-positive metastatic or locally advanced BC that progressed on or following a trastuzumab containing treatment	Open-label, non-randomized, Phase I/II	105	Safety/efficacy (see title)	Ongoing, not recruiting	

NCT00915018 NEFERTT	Study evaluating neratinib + paclitaxel vs trastuzumab + paclitaxel in ErbB2-positive advanced breast cancer	Women aged ≥ 18 years with HER2-positive locally recurrent or metastatic BC without prior systemic anticancer therapy other than endocrine therapy for locally recurrent or metastatic disease and no prior HER2 inhibitor other than trastuzumab or lapatinib in the neoadjuvant or adjuvant setting	Open-label, randomized, Phase II	480	Safety/efficacy, comparison of neratinib + paclitaxel vs trastuzumab + paclitaxel	Ongoing, not recruiting
NCT00706030	Study evaluating neratinib (HKI-272) in combination with vinorelbine in subjects with solid tumors and metastatic breast cancer	Women aged ≥ 18 years with confirmed pathologic diagnosis of a solid tumor that is not curable with available therapies (Part 1) or confirmed pathologic diagnosis of HER2-positive BC (current stage IV, Part 2) for which vinorelbine + neratinib is a reasonable treatment option and who had at least one prior antineoplastic chemotherapy for metastatic disease and at least one prior treatment with a trastuzumab-containing regimen or who relapsed under adjuvant treatment (Part 2 only)	Open-label, non-randomized, Phase I/II	92	Safety/efficacy of neratinib + vinorelbine, in Part 2 patients with or without prior lapatinib were included	Ongoing, not recruiting 80
NCT00300781	Study evaluating HKI-272 (neratinib) in subjects with advanced breast cancer	Women aged ≥ 18 years with advanced HER2-positive BC	Open-label, randomized, Phase II	137	Efficacy, cohort 1 patients that progressed on trastuzumab, cohort 2 patients with no prior trastuzumab	Ongoing, not recruiting 79
NCT01008150	Phase II randomized trial evaluating neoadjuvant therapy with neratinib and/or trastuzumab followed by postoperative trastuzumab in women with locally advanced HER2-positive breast cancer	Women aged ≥ 18 years with locally advanced HER2-positive BC without previous therapy with anthracyclines, taxanes, cyclophosphamide, trastuzumab, or neratinib for any malignancy	Open-label, randomized, Phase II	126	Safety/efficacy (Three arms: neratinib + paclitaxel \pm trastuzumab then doxorubicin and cyclophosphamide or paclitaxel + trastuzumab then doxorubicin and cyclophosphamide)	Recruiting
NCT01494662	HKI-272 for HER2-positive breast cancer and brain metastases	Patients aged ≥ 18 years with HER2-positive metastatic invasive BC who are not receiving other investigational agents, enzyme-inducing antiepileptic drugs, or any cancer-directed concurrent therapy Cohort 1: patients with new or progressive measurable CNS lesions Cohort 2: patients with CNS disease that is operable Cohort 3: patients with measurable CNS disease who a) had no prior lapatinib or b) had prior lapatinib	Open-label, non-randomized, Phase II	105	Efficacy (see patient cohorts)	Recruiting

(Continued)

Table 2 (Continued)

NCT identifier	Title	Study participants	Study design	Patients (n)	Objectives	Status	Reference
NCT01670877	Neratinib in metastatic HER2-negative but HER2-mutant breast cancer	Patients aged ≥ 18 years with stage IV, HER2-negative BC carrying a HER2 mutation with disease progression and not receiving any other investigational agents or systemic cancer therapy	Open-label, Phase II	29	Efficacy study (see title)	Recruiting	
NCT01808573	A study of neratinib + capecitabine vs lapatinib + capecitabine in patients with HER2-positive metastatic breast cancer who have received two or more prior HER2-directed regimens in the metastatic setting	Patients aged ≥ 18 years with confirmed HER2-positive metastatic BC, stage IV, with prior treatment with at least two (2) HER2-directed regimens for metastatic BC (except HER2-targeting TKIs)	Open-label, randomized, Phase III	600	Safety/efficacy (see title)	Recruiting	
NCT0111825	Temsirolimus + neratinib for patients with metastatic HER2-amplified or triple negative breast cancer	Patients aged ≥ 18 years with metastatic HER2-positive BC progressed on trastuzumab or lapatinib or metastatic triple negative invasive adenocarcinoma who do not receive any concurrent anticancer therapy or investigational agents	Open-label, non-randomized, Phase I/II	65	Safety/efficacy	Recruiting	

Note: ClinicalTrials.gov entries as of December 2014 are listed.

Abbreviations: BC, breast cancer; CNS, central nervous system; EGFR, epidermal growth factor receptor; TKIs, tyrosine kinase inhibitors; vs, versus.

enhance the response of TNBC cells to neratinib.⁶³ However, despite the promising in vitro data, TNBC patients did not have a statistically significant improvement in pathological complete response (pCR) when treated with neratinib and chemotherapy in comparison with chemotherapy alone in the I-SPY 2 trial (see below).⁶⁴ Moreover, a few trials involving cetuximab, an EGFR-targeting monoclonal antibody, have shown a poor response rate in patients with TNBC.^{65,66}

This indicates that TNBC tumors are heterogeneous and may be driven by several different oncogenes other than EGFR. Therefore, targeting EGFR may only be suitable for a small subset of patients. Thus, the data so far show that the mechanisms of response and resistance to neratinib and other EGFR inhibitors in TNBCs are not well understood. There is therefore a need for further investigation of relevant predictive biomarkers for use of EGFR inhibitors in TNBC.

Role of neratinib in treatment of tumors with EGFR, HER2, HER3, or HER4 somatic mutations

EGFR

Previously, erlotinib and gefitinib have been found to be particularly effective against NSCLCs with EGFR mutations, including L858R EGFR mutation.⁶⁷ However, secondary resistance is common due to an alternative T790M mutation, which causes increased affinity for ATP. However, this can be overcome by irreversible TKIs like afatinib, as they are not in a competitive equilibrium with ATP.⁶⁸ Two trials have demonstrated the clinical benefit of afatinib in patients with lung cancer who had progressed on erlotinib or gefitinib.^{69,70} The recent results from the LUX-Lung 3 trial showed superiority of afatinib with regard to response rate and progression-free survival over cisplatin and pemetrexed as first-line agents in treatment-naïve patients with advanced adenocarcinoma of the lung and EGFR mutation.⁷¹ Since then, afatinib has been approved for use in NSCLC with EGFR mutation. Since neratinib is a similar compound to afatinib as an irreversible TKI, there is an interest in assessing whether neratinib could be effective in solid tumors (including breast cancer) with EGFR mutations or amplification, and this is the basis for the Basket Study (NCT01953926, see below).

HER2

Similarly, neratinib could also be a treatment option for patients who carry a mutation in the HER2 protein. A recent publication evaluated data from eight breast cancer genome sequencing projects and identified a total of 13 somatic HER2 mutations, including seven activating mutations.⁷²

This analysis showed that approximately 1.6% of all newly diagnosed breast cancers may harbor a HER2 mutation, and most of these patients do not have HER2 gene amplification or overexpression.⁷² This percentage might be higher for patients who have relapsed. Interestingly, all functionally characterized mutations were sensitive to neratinib, including those that rendered cells resistant to lapatinib.⁷² This provides the rationale for testing neratinib in patients with HER2 mutations, including those with breast cancer.

HER3

Different studies have shown a 2%–4% prevalence of HER3 mutations in breast cancer with evidence for occurrence in other cancer types as well.⁷³ A majority of these somatic mutations were identified in the extracellular region. Although not by themselves, in combination with HER2, these mutations promoted oncogenic signaling and enhanced colony formation and *in vivo* growth. However, several HER3 or HER2 targeting agents, including trastuzumab and lapatinib, were effective in targeting these mutants,⁷³ indicating that neratinib may also have an effect.

HER4

HER4 mutations have been found in 19% of patients with melanoma.⁷⁴ A majority of these mutations are in the extracellular domain of HER4 and affect, for example, ligand binding. HER4 mutations were found to increase kinase activity and transformation ability.⁷⁴ Interestingly, melanoma cells with a HER4 mutation were sensitive to treatment with lapatinib.⁷⁴ As a result, lapatinib has been taken into clinical trials in melanoma, where patients with no more than two oncogenic somatic HER4 mutations will be offered lapatinib monotherapy (NCT01264081). Being an irreversible pan-HER inhibitor, neratinib could probably inhibit HER4 activation more effectively than lapatinib, although a head-to-head comparison trial has not been done. It will be interesting to assess whether neratinib is effective in tumors with HER4 mutations, including melanoma and breast cancer.

Proposed resistance mechanisms

Despite the encouraging results, experience has shown that single treatment with targeting agents frequently triggers resistance mechanisms. Therefore, work is underway to investigate potential counteracting pathways that come into action during treatment with neratinib.

One *in vitro* study used a pool-based lentiviral genome-wide functional RNA interference screen to discover genes which, if low or absent, would confer resistance to neratinib.

Interestingly, the screen identified, among others, genes involved in oncogenesis, transcription factors, as well as genes known to interact with breast cancer-associated genes,⁷⁵ highlighting the complexity of the cell machinery. One gene implicated was insulin-like growth factor binding protein 1, part of the insulin-like growth factor 1 pathway.⁷⁵ Another group identified miR-630 deficiency as a cause of neratinib resistance, at least partly due to its regulation of the insulin-like growth factor 1 receptor.⁷⁶ Recently, expression of the neuropeptide neuromedin U was associated with a poor prognosis in HER2-overexpressing breast cancer and has been shown to correspond with resistance to HER-targeting agents, including neratinib *in vitro*. It was suggested that neuromedin U acts through the chaperone heat shock protein 27 to aid HER2 stability.⁷⁷ As with lapatinib,⁴⁶ we observed a reactivation of HER3 and AKT phosphorylation after 24 hours of neratinib treatment in HER2-positive breast cancer cells, although we did not assess whether this was NRG1-dependent.²⁶ In addition, our previous work showed that ADAM10 was upregulated in neratinib-treated breast cancer cells, albeit to a lesser extent compared with trastuzumab-treated cells;⁴³ however, a thorough investigation was not carried out. Thus, it may be important to investigate whether HER ligand release mediated by ADAM10 and/or 17, a resistance mechanism found in trastuzumab,^{42,43} also mediates acquired resistance to neratinib.

Biomarkers

Biomarker studies *in vitro* have identified several potential biomarkers, including HER2, AKT, ERK, and other potential markers for response to neratinib (see HER2-positive breast cancer section above). However, there are not much data available from clinical trials as yet. So far, the I-SPY 2 trial has shown that neratinib in addition to standard neoadjuvant chemotherapy may be beneficial for patients with HER2-positive breast cancer, and in particular for those who have hormone receptor-negative disease (pCR rate 56% vs 33% for patients treated with standard chemotherapy alone).⁶⁴ Patients with hormone receptor-positive/HER2-positive disease also had a higher pCR rate with the addition of neratinib (30% vs 17%).⁶⁴ In the same study, patients were stratified according to their MammaPrint score (based on the median score of the I-SPY 1 trial). Patients with a higher score than the previous median MammaPrint score had a pCR of 47.5% if treated with a neratinib-containing regimen in comparison with 29.4% if treated with chemotherapy alone. Interestingly, 80.5% of these patients were negative for HER2. Nevertheless, patients with TNBC did not seem to benefit;⁶⁴ however, this subtype of

breast cancer is heterogeneous and other factors in addition to hormone receptor and HER2 status may be important. Further preclinical work as well as translational research using historical and prospective tumor samples from clinical trials will be needed to establish reliable biomarkers for neratinib response and resistance.

Clinical trials

Neratinib is currently being tested in various clinical trials for its safety and efficacy in various types of tumors, including NSCLC, colorectal, bladder and breast cancers. The trials that have been registered with Clinicaltrials.gov as of December 2014 are listed in Table 3. However, in this section, the main focus is on trials involving patients with breast cancer (Table 2).

Clinical trials in breast cancer

A Phase I dose-escalation study examined the safety and efficacy of neratinib at doses of 40–400 mg daily in patients with solid tumors. The absorption of neratinib was measured as median time to peak plasma concentration over 3–6.5 hours. The steady-state peak plasma concentration and area under the concentration–time curve for neratinib increased in a dose-dependent manner from 40 to 320 mg, but plateaued at higher doses.⁷⁸ Patients who received 40, 80, or 120 mg experienced no dose-limiting toxicities. This study determined the maximum tolerated dose at 320 mg, with 240 mg being the therapeutic dose.

In this dose-escalation study, 25 patients with breast cancer were evaluated for treatment efficacy; a partial response was observed in eight patients (32%), and stable disease for ≥ 24 weeks was found in one patient. The majority of responders had HER2-positive disease (IHC score 3+) and all had previously received trastuzumab, anthracyclines, and taxanes.⁷⁸

Neratinib monotherapy in patients with HER2-positive advanced breast cancer was associated with a 16-week progression-free survival rate of 59% with a median progression-free survival of 22.3 weeks in patients who had received prior trastuzumab treatment; and a rate of 78% with a median progression-free survival of 39.6 weeks in patients who were trastuzumab-naïve. The objective response rates were 24% in patients with prior trastuzumab treatment and 56% in the trastuzumab-naïve cohort.⁷⁹ Similarly, a Phase I/II study exploring the combination of neratinib with vinorelbine in pretreated HER2-positive metastatic breast cancer showed an objective response of 8% in patients with prior lapatinib and 41% in patients who had no prior lapatinib,

which was also mirrored in the respective progression-free survival rates.⁸⁰

On the other hand, neratinib in combination with paclitaxel showed an overall response rate of 71% in patients who had not previously been treated with lapatinib and 77% in those with prior lapatinib.⁸¹ However, the number of patients in this trial was small. Overall, the combination was found to have increased toxicity but it achieved a better response rate relative to neratinib monotherapy. The overall response rate was 73% (95% confidence interval 62.9–81.2); seven patients (7%) had a complete response and another nine patients (9%) had stable disease for ≥ 24 weeks. The median progression-free survival was 57.0 weeks (95% confidence interval 47.7–81.6).⁸¹

Another study compared the combination of neratinib with weekly paclitaxel and trastuzumab in heavily pretreated patients with HER2-positive metastatic breast cancer and showed an overall clinical benefit (complete response + partial response + stable disease ≥ 24 weeks) in eleven patients (52%) with a median time to disease progression of 3.7 months.⁸² The addition of neratinib and/or trastuzumab to neoadjuvant paclitaxel followed by doxorubicin and cyclophosphamide chemotherapy is currently being tested in a Phase II randomized trial (ClinicalTrials.gov identifier NCT 01008150).⁸² Neratinib in combination with the mammalian target of rapamycin inhibitor temsirolimus was found to be tolerable and to be potentially beneficial in HER2-positive, trastuzumab-resistant breast cancer and HER2-mutant NSCLC in a Phase I study; however, numbers were small.⁸³

Throughout the studies, the most common adverse event was diarrhea of any grade (up to 93%), especially during the first week of treatment; other adverse events included nausea, fatigue, vomiting, neutropenia, and anorexia.^{79,81} In the initial dose-escalation study, diarrhea (32%) was also the most common grade 3 or higher adverse event. In addition, it was the cause of dose reduction in 19 of 22 patients and was the adverse event that most frequently led to treatment discontinuation (14%).²⁶ This dose-escalation study suggested a potential relationship between neratinib dose/exposure and diarrhea,⁷⁸ but a follow-up study by Abbas et al revealed that there was no difference in the onset or severity of diarrhea in healthy subjects who were given neratinib either 240 mg once daily or 120 mg twice daily.⁸⁴ However, several studies have reported that diarrhea could be controlled with concurrent use of antidiarrheal agents.^{79,81} Thus, primary prophylactic use of antidiarrheal medication is now mandatory for all patients taking neratinib in recent

Table 3 Clinical trials involving neratinib in other cancers

NCT identifier	Title	Study subjects	Study design	Patients (n)	Objective	Status	Reference
NCT01142063	A single dose bioequivalence study of neratinib in healthy subjects	Healthy patients, aged 18–55 years	Phase I	28	Plasma concentration and half-life for neratinib, testing of bioequivalence of the two formulations	Completed	
NCT00860223	Study evaluating the potential effect of multiple doses of neratinib on the pharmacokinetics of a single dose of digoxin	Healthy patients, aged 18–50 years	Open-label, non-randomized, Phase I	27	Pharmacokinetics study (see title)	Completed	
NCT00380328	HKI-272 ketoconazole drug interaction study	Healthy subjects, aged 18–50 years	Open-label, randomized, Phase I	24	Pharmacokinetics, safety and tolerability	Completed	
NCT00498745	Study comparing 2 new formulations of HKI-272 in healthy adult subjects	Healthy subjects, aged 18–50 years	Open-label, randomized, Phase I	36	(see title)	Completed	
NCT00550212	Study evaluating oral administrations of HKI-272 in healthy male subjects	Healthy male subjects, aged 18–50 years	Open-label, non-randomized, Phase I	6	Pharmacokinetics (see title)	Completed	
NCT00366600	Study evaluating HKI-272 administered to healthy subjects	Healthy subjects, aged 18–50 years	Double-blind, randomized, Phase I	56	Pharmacokinetics; safety and tolerability; influence of food	Completed	
NCT00864487	Study evaluating the potential effect of rifampin on the pharmacokinetics of neratinib	Healthy subjects, aged 18–50 years	Open-label, non-randomized, Phase I	24	Pharmacokinetics (see title)	Completed	
NCT00814060	Study evaluating two tablet formulations of neratinib (HKI-272)	Healthy subjects, aged 18–50 years	Open-label, randomized, Phase I	24	Pharmacokinetics (see title)	Completed	
NCT00757809	Study evaluating the tolerability of multiple doses of HKI-272	Healthy subjects, aged 18–50 years	Double-blind, randomized, Phase I	50	Safety, occurrence of diarrhea (see title)	Completed	84
NCT00781430	Study evaluating the PK and safety of neratinib in healthy subjects and subjects with chronic liver disease	Healthy subjects, aged 18–65 years	Open-label, non-randomized, Phase I	27	Pharmacokinetics of neratinib in healthy subjects vs hepatically impaired patients/safety	Completed	
NCT00958724	Study evaluating neratinib in combination with vinorelbine in subjects with advanced or metastatic solid tumors	Patients aged ≥ 20 years with a solid tumor that is not curable with available therapies for which neratinib + vinorelbine is a reasonable treatment option	Open-label, non-randomized, Phase I	6	Safety/pharmacokinetics/activity	Completed	
NCT00768469	Study evaluating safety and tolerability, solid tumor	Patients aged ≥ 20 years with confirmed pathologic diagnosis of a solid tumor that is not curable with available therapy for which HKI-272 + paclitaxel is a reasonable treatment option	Open-label, Phase I	10	Safety and tolerability of neratinib + paclitaxel; pharmacokinetics and activity	Completed	

(Continued)

Table 3 (Continued)

NCT identifier	Title	Study participants	Study design	Patients (n)	Objective	Status	Reference
NCT00266877	Study evaluating the safety of HKI-272 (neratinib) in subjects with advanced NSCLC	Patients aged \geq 18 years with pathologic diagnosis of advanced NSCLC, not curable with conventional therapy	Open-label, non-randomized, Phase II	172	Efficacy: three arms A, B: patients with or without an EGFR mutation that have progressed on erlotinib or gefitinib C: previous smokers without prior EGFR TKI treatment	Completed	83
NCT00838539	Study evaluating neratinib in combination with temsirolimus in subjects with solid tumors	Patients aged \geq 18 years with pathologic diagnosis of incurable advanced or metastatic solid tumor who progressed on at least one conventional or standard therapy	Open-label, non-randomized, Phase I	63	Safety/pharmacokinetics and dosing of combination (see title)	Completed	83
NCT00397046	A study of the safety and tolerability of HKI-272 administered orally to Japanese subjects with advanced solid tumors	Patients aged \geq 20 years with metastatic or advanced cancer that has failed standard therapy	Open-label, non-randomized, Phase I	21	Safety/efficacy (see title)	Completed	89
NCT01956253	Single subject neratinib in bladder cancer	One patient with metastatic bladder cancer harboring a HER2-GRB7 gene fusion	Open-label, non-randomized	1	Response	Ongoing, not recruiting	
NCT01827267	Neratinib with and without temsirolimus for patients with HER2-activating mutations in NSCLC	Patients aged \geq 18 years with histologically confirmed advanced or metastatic HER2-mutant NSCLC without prior treatment with any investigational agent or neratinib or mTOR inhibitor	Open-label, randomized, Phase II	104	Safety/efficacy	Ongoing, not recruiting	
NCT01960023	Safety and efficacy study of neratinib and cetuximab to treat patients with quadruple wild-type metastatic colorectal cancer	Patients aged \geq 18 years with KRAS, NRAS, BRAF, PIK3CA wild-type	Open-label, Phase I/II	70	Safety/efficacy (see title)	Recruiting	
NCT01953926 Basket	An open-label, Phase II study of neratinib in patients with solid tumors with somatic human epidermal growth factor receptor (EGFR, HER2, HER3) mutations or EGFR gene amplification	Patients aged \geq 18 years with solid tumors with activating HER2, HER3 or EGFR mutations or with EGFR gene amplification without prior treatment with any pan-HER TKI	Open-label, non-randomized, Phase II	180	Safety/efficacy (see title)	Recruiting	

Note: ClinicalTrials.gov entries as of December 2014 are listed.

Abbreviations: EGFR, epidermal growth factor receptor; mTOR, mammalian target of rapamycin; NSCLC, non-small cell lung cancer; TKI, tyrosine kinase inhibitor; vs, versus.

clinical trials, which has helped to reduce the incidence of diarrhea.

A common side effect of anti-HER2 treatments, including trastuzumab, is cardiac in nature, ie, a decrease in left ventricular ejection fraction. Neratinib was investigated in healthy subjects with regard to its effect on cardiac repolarization and was shown not to prolong the QTc interval in comparison with controls.⁸⁵ However, the possible long-term cardiac toxicity from addition of neratinib to trastuzumab and/or chemotherapy will not be known until the ongoing clinical trials yield mature safety data.

Ongoing trials

Since neratinib was often more potent than lapatinib in the preclinical setting, there is interest in comparing the clinical efficacy of these two TKIs. Neratinib monotherapy has previously been compared with the combination of lapatinib and capecitabine; however, this study could determine neither inferiority nor noninferiority of neratinib.⁸⁶ Overall survival was slightly better in the lapatinib + capecitabine arm, but this difference was not statistically significant.⁸⁶ In addition, neratinib monotherapy may not be directly comparable with a combination of lapatinib and chemotherapy since the anti-HER2 treatment response could be enhanced by addition of concurrent chemotherapy. A subsequent study comparing neratinib + capecitabine with lapatinib + capecitabine in patients with HER2-positive metastatic breast cancer who have received two or more prior HER2-directed regimens in the metastatic setting (ClinicalTrials.gov identifier NCT01808573, NALA) is currently ongoing.

The ExteNET trial is comparing extended adjuvant neratinib vs placebo in HER2-positive patients with prior adjuvant trastuzumab. The primary endpoint is disease-free survival, which was increased by 33% in the neratinib arm (hazard ratio 0.67, $P=0.0046$) compared with the placebo arm. With regard to the secondary endpoint, ie, disease-free survival including for ductal carcinoma in situ, there was a 37% improvement in the neratinib arm compared with the placebo arm (hazard ratio 0.63, $P=0.0009$). Full results are expected soon. However, based on these results, Puma Biotechnology is planning to apply for approval of neratinib in the extended adjuvant setting in the first half of 2015.⁸⁷ In view of the effect of neratinib on HER receptor somatic mutations (see above), Puma Biotechnology has started an open-label Phase II study of neratinib in patients with solid tumors carrying somatic mutations of EGFR, HER2 or HER3, or EGFR gene amplification (BASKET study).⁸⁸

Conclusion

Neratinib is a potent, irreversible, pan-HER inhibitor that has shown promising activity in preclinical as well as clinical studies with an acceptable safety profile in humans. However, further elucidation is needed to determine when and in which combination this compound should be used. Although most studies showed that neratinib offers the greatest benefit to patients with HER2-positive breast cancer, some data indicate that some HER2-negative patients may also benefit. Moreover, neratinib is now being tested in many solid tumors carrying EGFR, HER2, or HER3 mutations, or EGFR amplification. It will be interesting to see where neratinib will be positioned in relation to other available HER-targeting antibodies as well as TKIs. Ongoing studies will help to better define patients likely to benefit most from neratinib-containing treatments and the associated predictive biomarkers.

Disclosure

The authors report no conflicts of interest in this work.

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