Breast Cancer - Targets and Therapy

Dovepress
open access to scientific and medical research

Open Access Full Text Article

REVIEW

Profile of palbociclib in the treatment of metastatic breast cancer

This article was published in the following Dove Press journal:
Breast Cancer - Targets and Therapy
17 May 2016
Number of times this article has been viewed

Moataz Ehab[1]
Mohamad Elbaz[2,3]

[1]Department of Pharmacy Practice, [2]Department of Pharmacology, Pharmacy School, Helwan University, Egypt; [3]Department of Pathology, The Comprehensive Cancer Center, The Ohio State University Wexner Medical Center, Columbus, OH, USA

Abstract: Breast cancer is the most common cancer diagnosed in women. Each year, thousands die either because of disease progression or failure of treatment. Breast cancer is classified into different subtypes based on the molecular expression of estrogen receptor (ER), progesterone receptor, and/or human epidermal growth factor receptor 2 (HER2). These receptors represent important therapeutic targets either through monoclonal antibodies or through small-molecule inhibitors directed toward them. However, up to 40% of patients develop either a primary or a secondary resistance to the current treatments. Therefore, there is an urgent need for investigating new targets in order to overcome the resistance and/or enhance the current therapies. Cell cycle is altered in many human cancers, especially in breast cancer. Cyclin-dependent kinases (CDKs), especially CDK4 and CDK6, play a pivotal role in cell cycle progression that makes them potential targets for new promising therapies. CDK inhibition has shown strong antitumor activities, ranging from cytostatic antiproliferative effects to synergistic effects in combination with other antitumor drugs. In order to overcome the drawbacks of the first-generation CDK inhibitors, recently, new CDK inhibitors have emerged that are more selective to CDK4 and CDK6 such as palbociclib, which is the most advanced CDK4/6 inhibitor in trials. In preclinical studies, palbociclib has shown a very promising antitumor activity, especially against ERα+ breast cancer subtype. Palbociclib has gained world attention, and US the Food and Drug Administration has accelerated its approval for first-line treatment in combination with letrozole for the first-line systematic treatment of postmenopausal women with ERα+/HER2− locally advanced or metastatic breast cancer. In this review, we discuss the potential role of CDK inhibition in breast cancer treatment, and focus on palbociclib progress from preclinical studies to clinical trials with mentioning the most recent ongoing as well as planned Phase II and Phase III trials of palbociclib in advanced breast cancer.

Keywords: cyclin-dependent kinases, cell cycle, metastatic breast cancer, PD0332991

Introduction

A million and a half new cases of breast cancer are reported annually around the world.[1] In the US, breast cancer is the most common cancer diagnosed in women, with an estimated number of 231,840 new cases in 2015.[2] It accounts for 29% of the total cancers among women with 40,290 estimated deaths, ranking second in the cancer mortality list in women.[2] Breast cancer is a heterogeneous disease with different clinical and biological behaviors. Although it affects the same anatomical organ, it has different clinical manifestations, etiology, prognosis, clinical outcomes, and responds differently to treatment.[3] The therapeutic options vary from primary surgery to targeted

Correspondence: Mohamad Elbaz
Department of Pathology,
The Comprehensive Cancer Center,
The Ohio State University Wexner Medical Center, 840 Biomedical Research Tower, 460 West 12th Avenue,
Columbus, OH 43210, USA
Tel +1 614 500 0948
Email elbaz.2@osu.edu

therapy, hormonal therapy, and/or chemotherapy; however, more studies and investigations need to be done for better and more effective treatment of breast cancer.[4]

Expression of hormonal receptors (HR), including estrogen receptor (ER), progesterone receptor (PR), and human epidermal growth factor receptor 2 (HER2), is used to classify breast cancers and aid in selecting appropriate treatment therapies.[5] Furthermore, breast cancers can be classified into luminal breast cancers expressing HR (such as ER and PR) and HER2 and basal-like cancers that lack expression of both HR and HER2.[6] Based on the previous classification, breast cancers can also be subdivided into five subtypes: Luminal A (HR+/HER2−), luminal B (HR+/HER2+), HER2-enriched (HR-/HER2+), basal-like (80%–90% are triple negative), and normal breast-like/unclassified breast cancers.[7,8]

ERα+ breast cancer accounts for ~70% of breast cancers, and most of ERα+ subtypes show a good response to hormonal therapy, including selective ER modulators and aromatase inhibitors.[9] Whereas the therapy of HER2+ cancers is based on targeting the overexpressed receptor with monoclonal antibodies.[5] On the other hand, triple-negative breast cancer (TNBC) (with negative expression of ER, PR, and HER2) is mostly treated with cytotoxic chemotherapeutic drugs.[10]

Metastatic breast cancer

Advanced breast cancer, also known as stage IV breast cancer, is a type of breast cancer that is usually referred to the metastatic status of the tumor, which means that the tumor cells have spread from their local site to the surrounding and then to other distant sites. Breast cancer metastasis is the most common cause of cancer-related death owing to the incurable nature of these metastases.[11,12] Metastatic disease develops in >20% of patients with early-stage breast cancer.[13] Approximately 75% of patients with metastatic breast cancers (MBCs) are HR+ with ERα+ and/or PR+.[14] In general, HR+ breast cancer subtypes usually develop late bone metastasis, whereas early visceral metastasis is usually due to TNBC.[15] Patients with MBC usually have median overall survival of 2–3 years from the time of their first diagnosis.[13] Generally, metastasis accounts for >90% of all cancer mortalities.[16]

Tamoxifen, anastrazole, and letrozole are the first-line hormonal therapies approved for HR+ MBC due to their high efficacy and tolerability.[9,17] Although hormonal therapy is effective in most patients with HR+ breast cancers, due to primary and secondary resistance, some patients will not respond to first-line hormonal treatment.[18] Therefore, a complete resistance to hormonal therapy is usually developed in ~40% of initial responder patients, and eventually they will depend totally on chemotherapy.[19,20] Furthermore, up to 30% of patients with breast cancer will relapse with metastasis.[21]

Hence, new targets have to be discovered, and new treatment therapies have to be studied in order to optimize the current therapies and improve patient outcomes. Studying the mechanisms of resistance to the current therapies has identified new possible targets to circumvent the resistance problem; such targets are cyclin-dependent kinase 4 and 6 (CDK4/6), phosphatidylinositol 3-kinase/mammalian target of rapamycin (PI3K/mTOR) pathway, and poly adenosine diphosphate ribose polymerase.[22]

Alterations of PI3K/mTOR genes occur in >80% of patients with breast cancer (28%–47% of ER+ breast cancers), and this pathway regulates many cellular processes that promote cell proliferation and metastasis.[22] Cell proliferation by PI3K might be promoted through the activation of ER by phosphorylation.[23] Interestingly, PI3K/mTOR pathway was reported to be upregulated in HR+ tumors that were resistant to endocrine therapy.[22]

Herein, we review the newly developed drug palbociclib and its impact on breast cancer, especially the metastatic disease.

CDK role in cell cycle

Cyclin D–CDKs–retinoblastoma (Rb) pathway drives cells through checkpoint in the cell cycle initiating the DNA replication and, hence, starting cell division.[24] DNA synthesis (S), mitotic (M), and gaps (G1 and G2) phases are the four phases of cell cycle. During G1 phase, cells reach a checkpoint when they decide whether to transit to (S) phase or quit the current cell cycle.[25] Alteration in cell cycle is one of the hallmarks of cancer.[26] The activation of CDKs by cyclin D proteins plays an important role in G1/S cell cycle transition by phosphorylation of Rb protein. Rb protein acts as a tumor suppressor controlling G1/S transition of cell cycle.[27] When Rb is phosphorylated, it loses its negative control on G1/S transition.[28] Hence, activating E2F family of transcription factors that allows DNA replication to start.[29] Cyclin D proteins provide a link between mitogenic signals and the machinery of cell cycle.[30] Interestingly, the enforced overexpression of cyclin D in cultured cells can shorten the G1 interval.[31] Therefore, increasing the replication capacity which might result in tumorigenesis.

The major role played by CDKs in cell cycle regulation was discovered for the first time in fission yeasts.[32] CDKs are serine/threonine-based kinases comprising numerous subtypes, divided into two main groups according to their functions. Mainly CDK2, CDK4, and CDK6 are involved

in cell cycle G1/S transition, while CDKs 7–11 function as transcriptional regulators.[24,33]

CDK4 and CDK6 have ~71% sequence homology, and both of them interact with the D-type cyclins (D1, D2, and D3).[34] INK4 proteins, such as p16, are endogenous CDK4/6 inhibitors; they inhibit cyclin D–CDK4/6 function through binding to CDK4/6 and reduce the affinity to cyclin D proteins.[35]

Recently, CDK6 was reported to promote the angiogenesis process. Moreover, CDK6 plays an important role in activating hemopoietic stem cells; thus, CDK6 inhibition may have an antiangiogenesis activity; however, myelosuppression is suspected to be a common side effect associated with selective CDK4/6 inhibitor therapy.[36,37]

Around 90% of human solid cancers were reported to have alterations in cyclin D–CDK–Rb pathway.[38] Alteration of such pathways can occur by different mechanisms, such as inactivation of p16 (happens in 50% of invasive breast cancers) and CDK4 mutations. Additionally, cyclin D1 was reported to be overexpressed in ~70% of breast cancer, and also overexpression of cyclin D1-encoding gene (*CCND1*) and CDK4 were characterized for breast cancer.[14,39]

Loss of Rb expression has been reported in ~20%–30% of breast cancers especially in TNBC. In addition, loss of Rb facilitates epithelial-to-mesenchymal transition process, thus, increasing the metastatic and invasive potential of breast cancer cells.[40,41]

CDK inhibitors

In the 1990s, first-generation CDK inhibitors were introduced in preclinical and clinical trials.[42] Flavopiridol (administrated as intravenous infusion), a nonselective first-generation CDK inhibitor, was the first to enter clinical trials, and it was found to have different strong antitumor effects such as enhancing cell cycle arrest, in addition to its antiangiogenic, proapoptotic, and synergetic potential with antitumor chemotherapeutic agents.[43,44] However, due to their low therapeutic index, low sensitivity, and multitargets, first-generation CDK inhibitors have been discontinued.[45] Therefore, there is an urgent need for developing more selective CDK inhibitors. Palbociclib (PD0332991), abemaciclib (LY2835219), and ribociclib (LEE011) were then introduced as a new generation of CDK inhibitors with high selective inhibition to CDK4 and CDK6.[25]

Palbociclib

Palbociclib or PD0332991 was first introduced as a potent CDK4/6 inhibitor that has strong antitumor activity by Fry et al.[46] Palbociclib (brand name: Ibrance®) is an oral potent selective CDK4/6 inhibitor developed by Pfizer (NY, USA) (Figure 1).[47] PD0332991 blocks ATP binding to the CDK4/6 enzymes with half-maximal inhibitory concentration (IC50) 0.011 μmol/L for CDK4/cyclin-D1, 0.009 μmol/L for CDK4/cyclin-D3, and 0.015 μmol/L for CDK6/cyclin-D2 complexes.[38]

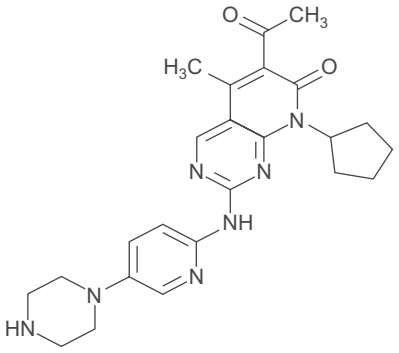

Figure 1 Chemical structure of palbociclib (PD0332991).

As we mentioned before, CDK4/6 inhibition can result in many pharmacological activities based on the different roles of these enzymes (Figure 2). It was expected that palbociclib would show strong antiproliferative and antiangiogenic activities. Currently, palbociclib is the most advanced selective CDK4/6 inhibitor in clinical development.[25]

Other than breast cancer, preclinical studies of palbociclib on different types of cancers showed a promising antiproliferative activity. Palbociclib successfully inhibited tumor proliferation in different cancer cell lines and xenograft mouse models including neuroblastoma,[48] glioblastoma,[49] colorectal carcinoma,[50] advanced Rb+ bladder cancer[51] gastric cancer,[52] and sarcomas.[53]

Preclinical trials

Among 47 human cell lines of different subtypes of breast cancer, ERα+ subtypes were found to be most sensitive to palbociclib growth inhibition.[54] ERα+ subtypes' sensitivity to CDK4/6 inhibitors may be due to the hyperactivation of cyclin D1 and CDK4/6 that was reported in those subtypes.[20,21] While in Rb-deficient MDA-MB-468 (ERα–) human breast cancer cell lines, palbociclib showed no antiproliferative effect.[46] Loss of Rb expression was reported to render the cancer cells resistant to CDK4/6 inhibition therapy.[49,55] p16 overexpression in Rb-deficient breast cancer cells might account for the resistance to palbociclib, as CDK4/6 enzymes were already inhibited by the overexpressed p16.[56] Interestingly, cyclin D1 overexpression and Rb phosphorylation in ERα+ cancers were reported to contribute to the resistance to the hormonal therapy.[42]

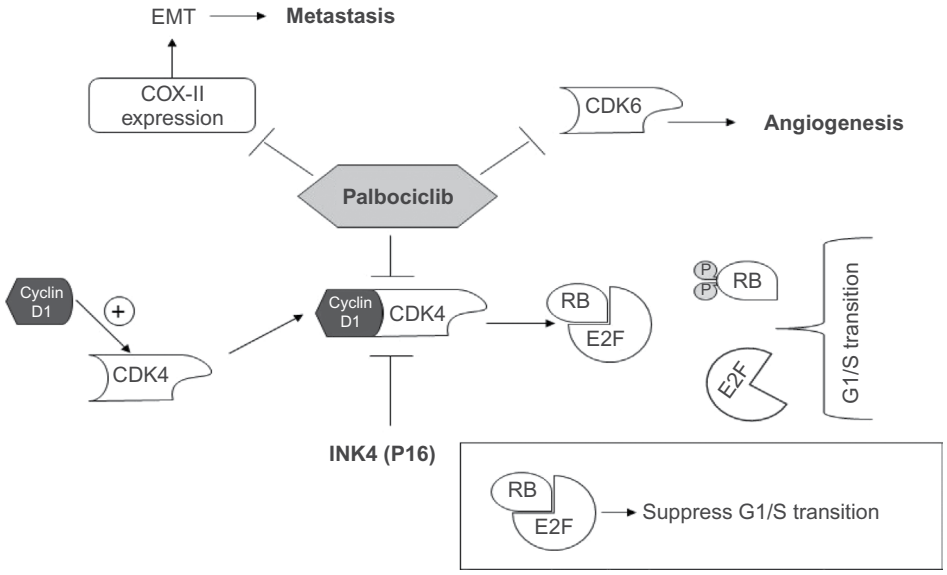

Figure 2 Palbociclib mechanism of action.
Notes: Cyclin D1 activated CDK4 and then the resultant complex phosphorylates retinoblastoma protein. G1/S transition depends on the release of E2F family of transcription factors after RB is phosphorylated (P). Palbociclib blocks G1/S transition by ultimately inhibiting RB phosphorylation. Another suggested effect of palbociclib is decreasing metastasis by decreasing expression of COX-II enzyme, which contributes in EMT process. EMT gives cells invasive and metastatic properties. Also, by blocking CDK6 that was reported to have a role in angiogenesis, palbociclib is suggested to have antiangiogenesis effect.
Abbreviations: CDK, cyclin-dependent kinase; COX-II, cyclooxygenase-II; EMT, epithelial-to-mesenchymal transition; RB, retinoblastoma protein.

Additionally, cyclin D1 is one of the ER transcriptional targets, thus, rationalizing the use of CDK4/6 inhibitors in ERα+ breast cancer.[57]

Besides antiproliferative activity, in MDA-MB-231 (ERα–) and T47D (ERα+) breast cancer cells, palbociclib has shown strong antimetastatic activity in a dose-dependent manner through reducing cyclooxygenase-II expression.[58] Cyclooxygenase-II has been reported to be associated with the activation of epithelial-to-mesenchymal transition process, which helps the epithelial cells to lose their epithelial characteristics and gain mesenchymal characteristics, therefore, increasing their invasive and metastatic potentials.[59,60] Moreover, CDK4/6 inhibition by palbociclib induced senescence in melanoma cell lines by promoting Forkhead Box M1 degradation.[61]

Furthermore, in two in vivo animal studies, palbociclib was found to be a substrate to efflux transporters P-glycated protein and breast cancer resistance protein. These transporters limit palbociclib delivery to the brain.[62,63] When adding elacridal (dual P-glycated protein and breast cancer resistance protein inhibitor) to palbociclib, the brain levels of palbociclib were increased significantly, therefore enhancing its efficacy in treating brain metastasis.[62] Breast cancer is highly metastatic to the brain, making it the second most common cause of brain metastasis; therefore, there is always a crucial need to enhance the crossing of antitumor drugs to the blood–brain barrier.[62] On the other hand, abemaciclib (LY2835219) reached brain at low doses, suggesting that it may offer a better activity in treating breast cancer brain metastasis.[64]

Clinical trials of hormonal therapy combination with CDK4/6 inhibitors were triggered when hormonal therapy resistance was observed to be linked with genes that are regulated through cyclin D–CDK–Rb pathway.[44] Moreover, apoptosis was observed to be increased, when cells were therapeutically arrested and then treated with hormonal therapy.[41] Therefore, controlling cell cycle by controlling cyclin D–CDK–Rb pathway using CDK4/6 inhibitors may have a synergistic activity when combined with hormonal therapies, as well as, reduce the resistance acquired to that class of treatment..

Clinical trials in breast cancer

Phase I trials

Schwartz et al[65] conducted the first Phase I study of palbociclib in humans to determine maximum tolerated dose (MTD) and dose-limiting toxicities (DLTs) of the 2/1 schedule of palbociclib treatment (2 weeks once daily and 1 week off treatment). Patients with non-Hodgkin's lymphoma and/or Rb+ advanced solid tumor were eligible for this study. Six patients, out of the 33 enrolled patients, experienced DLT. Myelosuppression was the common adverse effect including neutropenia (grade 3) that occurred in 24% of patients, whereas nonhematological toxicity was of mild-to-moderate

Table 1 Palbociclib pharmacokinetic parameters for 2/1 schedule and 3/1 schedule

Pharmacokinetic parameter	2/1 Schedule (SS, dose 200 mg)	3/1 Schedule (SS, dose 125 mg)
T_{max}, h	4.2	5.5
V_z/F, L	3,241	2,793
$T_{1/2}$, h	26.7	26
CL/F, L/h	88.5	80.6
Rac	2.4	2.2
Reference	Schwartz et al[65]	Flaherty et al[66]

Notes: T_{max}, time to maximum plasma concentration; V_z/F, apparent volume of distribution; $T_{1/2}$, elimination half-life; CL/F, apparent clearance; Rac, accumulation ratio; 3/1 Schedule, 3 weeks once daily and 1 week off treatment; 2/1 Schedule, 2 weeks once daily and 1 week off treatment.
Abbreviations: h, hours; SS, steady state.

intensity including fatigue, diarrhea, and constipation. Moreover, the MTD was found to be 200 mg once daily.[65]

Another Phase I study by Flaherty et al[66] identified the DLT and MTD for the 3/1 schedule of palbociclib treatment (3 weeks once daily and 1 week off treatment). The enrolled 41 patients had Rb+ advanced solid tumors (five patients had breast cancer). The MTD was found to be 125 mg once daily. Only five patients had DLTs; neutropenia (grade 3, 12%) was the most common, while nonhematological adverse events were fatigue, diarrhea, and nausea. These results were consistent with the results of the Phase I study of Schwartz et al[65], and both of the studies showed that palbociclib was well tolerated and neutropenia was the only significant DLT.[66] Besides the MTD and DLTs, Schwartz et al[65] and Flaherty et al[66] determined the pharmacokinetic parameters of palbociclib for the 2/1 schedule and 3/1 schedule (Table 1).

Phase II trials

DeMichele et al[67] studied palbociclib in a Phase II trial as a single agent in advanced breast cancer. Eligible patients were confirmed to have Rb-positive MBC, and of the 37 enrolled patients, 33 patients were HR+ (7% ERα+, 4% PR+, and 22% ERα+/PR+).[67] Clinical benefit ratio was 21% for patients with HR+ and 29% for patients with HR+/HER2− who were exposed to least two prior lines of hormonal therapy. Progression-free survival (PFS) was significantly longer for patients with HR+ rather than HR− (P=0.03). On the other hand, patients exposed to chemotherapy with fewer than two prior therapies had greater clinical benefit ratio than those exposed to heavy treatment.[67] Most adverse events were mostly cytopenias due to myelosuppression. Neutropenia (grade 3/4) was the most frequently occurring cytopenia with 51% of patients, and it was the reason for 46% of all dose modifications. Although neutropenia was common, neutropenic fever/infection was rare, suggesting that bone marrow progenitors were only suppressed during treatment but still functioning in infections.[67] According to the presented results, palbociclib could be effective as a single agent, but more trials have to be conducted with larger sample size to confirm the applicability and efficacy of palbociclib as a single agent in MBC. Similarly, the other selective CDK4/6 inhibitors, abemaciclib and ribociclib, as well, showed a significant clinical activity in ER+ breast cancer in early clinical studies.[68]

Finn et al[1,69] conducted the PALOMA-1/TRIO-18 trial; PALOMA-1 was a Phase I/II study. In Phase I, nine postmenopausal women with ERα+/HER2− breast cancer were enrolled to assess the safety, tolerability, and drug–drug interactions of combining palbociclib with letrozole. The combination was well tolerated and encouraged the Phase II of the study. Phase II was a randomized, open-label trial conducted on 165 eligible patients who were postmenopausal with advanced ERα+/HER2− breast cancer and never had any systematic treatment. This Phase II study assessed the efficacy of combination of palbociclib with letrozole versus letrozole alone.

The combination therapy showed a significant improvement in the PFS (primary end point) of 10 months longer in combination group (20.2 months) than letrozole alone group (10.2 months) (hazard ratio 0.488, 95% confidence interval [CI] 0.319–0.748; one-sided P=0.0004).[1] Neutropenia (54% for grade 3/4), leukopenia (43% all grades), and fatigue (40% all grades) were the most common adverse events reported for the combination group (n=83). Febrile neutropenia had not occurred in any of the patients in the combination group.[1] In the same study, amplification of cyclin D1 and loss of p16 did not show any benefit as biomarkers for CDK4/6 inhibition treatment patients' selection.[1]

PALOMA-1 showed a significant improvement in the PFS when palbociclib was combined with letrozole. Thus, after the results were published, palbociclib received breakthrough therapy designation from US Food and Drug Administration (FDA) in April 2013.[70] In February 2015, palbociclib received FDA accelerated approval for use in combination with letrozole for the first-line treatment of postmenopausal women with ERα+/HER2− locally advanced breast cancer or MBC.[17,70] Apart from breast cancer, a Phase II trial conducted on liposarcoma showed an improved PFS when patients were treated with palbociclib.[71]

Phase III trials

PALOMA-3, a randomized, double-blinded, Phase III study, involving 521 patients with advanced breast cancer, was conducted by Turner et al.[72] The efficacy of palbociclib in combination with fulvestrant versus fulvestrant alone

was assessed, and PFS was the primary end point. Eligible patients had advanced HR+/HER2− breast cancer and had relapsed or progressed disease during prior hormonal therapy. The PFS was improved in palbociclib/fulvestrant group (9.2 months) more than the median PFS of fulvestrant alone group (3.8 months) (hazard ratio for disease progression or death, 0.42; 95% CI, 0.32–0.56; $P<0.001$).[72]

The adverse events were consistent with the previous studies with neutropenia (occurred in 62% of patients) as the major adverse event, and only 0.6% of patients experienced febrile neutropenia. Finally, the ongoing and planned Phase II and Phase III clinical trials of palbociclib in MBC are presented in Table 2.

Palbociclib in combination with chemotherapy

Since TNBC has no target and its treatment depends on chemotherapy, the combination of palbociclib to cytotoxic chemotherapy has to be assessed as to whether it will have additive or antagonistic effects to the cancer chemotherapy.

In a preclinical study using Rb-proficient TNBC (MDA-MB-231 and Hs578T) cells, palbociclib when combined with anthracycline "doxorubicin" was found to antagonize doxorubicin cytotoxic effects. Additionally, in mice with Rb-proficient MDA-MB-231 xenografts, the cytotoxic effects of doxorubicin were inhibited upon co-administration of palbociclib. Moreover, the authors assessed the dependence of palbociclib on Rb expression status; they repeated the same in vivo experiment but used Rb-deficient MDA-MB-231 xenografts and found that palbociclib had no effect on cytotoxic effects of doxorubicin efficacy, suggesting that Rb expression is essential for palbociclib cytostatic activity.[10]

In another study, the impact of combining palbociclib with taxane and anthracycline chemotherapies was assessed using TNBC Rb-proficient MDA-MB-231 and Hs578T breast cancer cell models. The results of the combination were consistent with the previous study; palbociclib was found to antagonize their cytotoxic effects, suggesting that palbociclib altered DNA repair, blocked the chemotherapy-induced cell damage, and prevented cell death.[73] In another in vivo study on genetically engineered murine models of Rb-proficient (MMTV-c-neu) and Rb-deficient (C3-TAg) mice, it was found that combining palbociclib with carboplatin resulted in decreased cytotoxic activity versus carboplatin alone in the Rb-proficient MMTV-c-neu mice. On the other hand, Rb-deficient (C3-TAg) mice were resistant to palbociclib and the combination therapy showed no antagonistic effect to carboplatin cytotoxicity.[74]

Interestingly and in contrast, paclitaxel cytotoxicity was found to be increased when cells were synchronized after short exposure to palbociclib (24 hours) prior to paclitaxel treatment. These observations suggest that the duration and the time of administration of palbociclib are important and should be considered carefully when we combine palbociclib with chemotherapies.[73] Based on the last observation, a Phase I trial of palbociclib and paxlitaxel combination was conducted, and the combination was found to be safe and well tolerated.[75] Overall, we should wait for the results of the upcoming trials to determine the efficacy of these combinations in clinical practice.

Conclusion and future directions

Breast cancer is not a single disease; it is a set of different heterogeneous diseases that affect one anatomical organ. Major progress and discoveries have been made in breast cancer field; but unfortunately, breast cancer still has high incidence and limited therapeutic options. Current therapies are well tolerated and of high efficacy, but unfortunately, some patients develop resistance and relapse to more advanced and metastatic disease. Thus, the urge for developing new treatments is crucial. The extensive analysis of the resistance and its mechanisms are needed to discover new promising targets. CDKs are one of the most promising new therapeutic targets. First-generation CDK inhibitors showed good antitumor activities in preclinical studies; however, they show a serious high toxicity due to their lack of specific targets. Therefore, new selective CDK4/6 inhibitors have emerged to overcome this drawback. Palbociclib is the most advanced member in this new generation of CDK4/6 inhibitors.

Preclinical data confirmed palbociclib antitumor activity in multiple tumors. In addition, Phase I studies showed its efficacy tolerability and safety, which encouraged going to the next step in clinical trials. Reversible neutropenia is the only significant adverse event for palbociclib, and fortunately, it can be managed easily by dose adjusting without affecting the efficacy. Palbociclib in combination with hormonal therapy (letrozole) gained FDA accelerated approval after PALOMA-1 results were published. This combination therapy showed a significant and remarkable improvement in PFS in postmenopausal women with ERα+/HER2− locally advanced breast cancer or MBC.

Until now, Rb protein is the only reliable indicator for palbociclib activity; in Rb-proficient cells, palbociclib showed antitumor activities, while in Rb-deficient/mutant cells, palbociclib lost its activity. We propose that Rb as an indicator is sufficient for now, in this early stage, for palbociclib applications, but in the future, we may have to find more

Table 2 Ongoing and future palbociclib trials

Study intervention	Phase	Study design	Status	Estimated completion date	Estimated enrollments	Patients setting	Primary end point	ClinicalTrials.gov identifier
Palbociclib/letrozole vs letrozole for first-line treatment (PALOMA-2)	III	Randomized double-blinded	Ongoing	February 2017	650	Postmenopausal women with ER+/HER2– ABC	PFS	NCT01740427
Palbociclib/exemestane/goserelin vs capecitabine	II	Randomized open-labeled	Not recruiting yet	September 2019	122	Premenopausal women with HR+ MBC	PFS	NCT02592746
Palbociclib in combination with tamoxifen as first-line therapy	II	Single arm open-labeled	Not recruiting yet	June 2019	71	HR+/HER2– MBC	RR	NCT02668666
Palbociclib/letrozole vs letrozole for first-line treatment (PALOMA-4)	III	Randomized double-blinded	Recruiting	October 2017	330	Asian postmenopausal women with ER+/HER2– ABC	PFS	NCT02297438
AZD2014 in combination with palbociclib (PASTOR)	I/II	Randomized double-blinded	Recruiting	May 2019	225	Postmenopausal women with ER+ MBC	MTD, RP2D, PFS	NCT02599714
Palbociclib/exemestane vs capecitabine (PEARL)	III	Randomized open-labeled	Recruiting	January 2018	348	HR+/HER2– MBC in patients resistant to NSAI	PFS	NCT02028507
Palbociclib and trastuzumab with or without letrozole (PATRICIA)	II	Randomized open-labeled	Recruiting	December 2019	138	Postmenopausal women with HER2+ MBC	PFS	NCT02448420
Palbociclib in combination with bicalutamide	I/II	Single arm open-labeled	Recruiting	November 2018	51	AR+ TNMBC	RP2D, PFS	NCT02605486
Palbociclib combined with fulvestrant or letrozole (PARSIFAL)	II	Randomized open-labeled	Recruiting	July 2018	304	HR+/HER2– MBC	PFS	NCT02491983
Palbociclib in combination with fulvestrant or tamoxifen	II	Randomized open-labeled	Not recruiting yet	August 2017	70	HR+ MBC previously exposed to PI3Ki	TP	NCT02384239

Abbreviations: ABC, advanced breast cancer; AR, androgen receptor; ER, estrogen receptor; HER2, human epidermal growth factor receptor 2; HR, hormonal receptor; MBC, metastatic breast cancer; MTD, maximum tolerated dose; NSAI, nonsteroidal aromatase inhibitors; PFS, progression-free survival; PI3Ki, PI3K inhibitors; RR, response rate; RP2D, recommended Phase II dose; TNMBC, triple negative metastatic breast cancer; TP, tumor progression.

indicators and biomarkers to assess palbociclib efficacy and monitor its activities. Additionally, more preclinical studies have to be conducted on combining palbociclib with cytotoxic chemotherapeutic agents and cautiously assess the safety and efficacy of these combinations. Overall, palbociclib seems to be a very promising drug and carries a hope for millions of patients with breast cancer, especially those who suffer from late-stage metastasis.

Author contributions

Conception and design, data acquisition and analysis, and writing the manuscript: Moataz Ehab and Mohamad Elbaz. Study supervision: Mohamad Elbaz.

Disclosure

The authors report no conflicts of interest in this work.

References

1. Finn RS, Crown JP, Lang I, et al. The cyclin-dependent kinase 4/6 inhibitor palbociclib in combination with letrozole versus letrozole alone as first-line treatment of oestrogen receptor-positive, HER2-negative, advanced breast cancer (PALOMA-1/TRIO-18): a randomised phase 2 study. *Lancet Oncol*. 2014;16(1):25–35.
2. Siegel RL, Miller KD, Jemal A. American Cancer Society. Cancer Facts & Figures 2015. Atlanta: American Cancer Society; 2015;65(1):5–29.
3. Weigelt B, Geyer FC, Reis-Filho JS. Histological types of breast cancer: how special are they? *Mol Oncol*. 2010;4(3):192–208.
4. de Ruijter TC, Veeck J, de Hoon JPJ, van Engeland M, Tjan-Heijnen VC. Characteristics of triple-negative breast cancer. *J Cancer Res Clin Oncol*. 2011;137(2):183–192.
5. Matsumoto A, Jinno H, Ando T, et al. Biological markers of invasive breast cancer. *Jpn J Clin Oncol*. 2015;4:hyv153.
6. Darb-Esfahani S, Loibl S, Müller BM, et al. Identification of biology-based breast cancer types with distinct predictive and prognostic features: role of steroid hormone and HER2 receptor expression in patients treated with neoadjuvant anthracycline/taxane-based chemotherapy. *Breast Cancer Res*. 2009;11(5):R69.
7. Masood S. Breast cancer subtypes: morphologic and biologic characterization. *Womens Health (Lond Engl)*. 2016;12(1):103–119.
8. American Cancer Society. Breast Cancer Facts & Figures 2015–2016. Atlanta: American Cancer Society, Inc. 2015.
9. Almstedt K, Schmidt M. Targeted therapies overcoming endocrine resistance in hormone receptor-positive breast cancer. *Breast Care*. 2015;10(3):168–172.
10. McClendon AK, Dean JL, Rivadeneira DB, et al. CDK4/6 inhibition antagonizes the cytotoxic response to anthracycline therapy. *Cell Cycle*. 2012;11(14):2747–2755.
11. Lu J, Steeg PS, Price JE, et al. Breast cancer metastasis: challenges and opportunities. *Cancer Res*. 2009;69(12):4951–4953.
12. Elbaz M, Nasser MW, Ravi J, et al. Modulation of the tumor microenvironment and inhibition of EGF/EGFR pathway: novel anti-tumor mechanisms of cannabidiol in breast cancer. *Mol Oncol*. 2015;9(4):906–919.
13. Mangini NS, Wesolowski R, Ramaswamy B, Lustberg MB, Berger MJ. Palbociclib: a novel cyclin-dependent kinase inhibitor for hormone receptor-positive advanced breast cancer. *Ann Pharmacother*. 2015;49(11):1252–1260.
14. O'Sullivan CC. Overcoming Endocrine Resistance in Hormone-Receptor Positive Advanced Breast Cancer-The Emerging Role of CDK4/6 Inhibitors. *Int J cancer Clin Res*. 2015;2(4).
15. Hudis CA, Gianni L. Triple-negative breast cancer: an unmet medical need. *Oncologist*. 2011;16(suppl 1):1–11.
16. Lawson DA, Bhakta NR, Kessenbrock K, et al. Single-cell analysis reveals a stem-cell program in human metastatic breast cancer cells. *Nature*. 2015;526(7571):131–135.
17. Beaver JA, Amiri-Kordestani L, Charlab R, et al. FDA approval: palbociclib for the treatment of postmenopausal patients with estrogen receptor-positive, HER2-negative metastatic breast cancer. *Clin Cancer Res*. 2015;21(21):4760–4766.
18. Ring A, Dowsett M. Mechanisms of tamoxifen resistance. *Endocr Relat Cancer*. 2004;11(4):643–658.
19. Yamamoto-ibusuki M, Arnedos M, André F. Targeted therapies for ER +/HER2- metastatic breast cancer. *BMC Med*. 2015;13:137.
20. Mayer EL. Targeting breast cancer with CDK inhibitors. *Curr Oncol Rep*. 2015;17(5):443.
21. Nagaraj G, Ma C. Revisiting the estrogen receptor pathway and its role in endocrine therapy for postmenopausal women with estrogen receptor-positive metastatic breast cancer. *Breast Cancer Res Treat*. 2015;150(2):231–242.
22. Hosford SR, Miller TW. Clinical potential of novel therapeutic targets in breast cancer: CDK4/6, Src, JAK/STAT, PARP, HDAC, and PI3K/AKT/mTOR pathways. *Pharmgenomics Pers Med*. 2014;7:203–215.
23. Hayashi S, Kimura M. Mechanisms of hormonal therapy resistance in breast cancer. *Int J Clin Oncol*. 2015;20(2):262–267.
24. Malumbres M, Barbacid M. To cycle or not to cycle: a critical decision in cancer. *Nat Rev Cancer*. 2001;1(3):222–231.
25. Murphy CG, Dickler MN. The role of CDK4/6 inhibition in breast cancer. *Oncologist*. 2015;20(5):483–490.
26. Hanahan D, Weinberg RA. The hallmarks of cancer. *Cell*. 2000;100(1):57–70.
27. Roesley SNA, Suryadinata R, Morrish E, et al. Cyclin-dependent kinase-mediated phosphorylation of breast cancer metastasis suppressor 1 (BRMS1) affects cell migration. *Cell Cycle*. 2016;15(1):137–151.
28. Lundberg AS, Weinberg RA. Functional inactivation of the retinoblastoma protein requires sequential modification by at least two distinct cyclin-cdk complexes. *Mol Cell Biol*. 1998;18(2):753–761.
29. Harbour JW, Dean DC. The Rb/E2F pathway: expanding roles and emerging paradigms. *Genes Dev*. 2000;14(19):2393–2409.
30. Ekholm SV, Reed SI. Regulation of G1 cyclin-dependent kinases in the mammalian cell cycle. *Curr Opin Cell Biol*. 2000;12(6):676–684.
31. Sherr CJ, Roberts JM. Living with or without cyclins and cyclin-dependent kinases. *Genes Dev*. 2004;18(22):2699–2711.
32. Nurse P, Masui Y, Hartwell L. Understanding the cell cycle. *Nat Med*. 1998;4(10):1103–1106.
33. Casimiro MC, Velasco-Velázquez M, Aguirre-Alvarado C, Pestell RG. Overview of cyclins D1 function in cancer and the CDK inhibitor landscape: past and present. *Expert Opin Investig Drugs*. 2014;23(3):295–304.
34. Liao Y, Feng Y, Shen J, Hornicek FJ, Duan Z. The roles and therapeutic potential of cyclin-dependent kinases (CDKs) in sarcoma. *Cancer Metastasis Rev*. 2015. Epub 2015 Dec 15.
35. Dukelow T, Kishan D, Khasraw M, Murphy CG. CDK4/6 inhibitors in breast cancer. *Anticancer Drugs*. 2015;26(8):797–806.
36. Kollmann K, Heller G, Schneckenleithner C, et al. A kinase-independent function of CDK6 links the cell cycle to tumor angiogenesis. *Cancer Cell*. 2013;24(2):167–181.
37. Scheicher R, Hoelbl-Kovacic A, Bellutti F, et al. CDK6 as a key regulator of hematopoietic and leukemic stem cell activation. *Blood*. 2015;125(1):90–101.
38. Altenburg JD, Farag SS. The potential role of PD0332991 (palbociclib) in the treatment of multiple myeloma. *Expert Opin Investig Drugs*. 2015;24(2):261–271.
39. Peurala E, Koivunen P, Haapasaari K-M, Bloigu R, Jukkola-Vuorinen A. The prognostic significance and value of cyclin D1, CDK4 and p16 in human breast cancer. *Breast Cancer Res*. 2013;15(1):R5.
40. Konecny GE. Cyclin-dependent kinase pathways as targets for women's cancer treatment. *Curr Opin Obstet Gynecol*. 2016;28(1):42–48.

41. Cadoo KA, Gucalp A, Traina TA. Palbociclib : an evidence-based review of its potential in the treatment of breast cancer. *Breast Cancer (Dove Med Press)*. 2014;4(6):123–133.
42. Tamura K. Development of cell-cycle checkpoint therapy for solid tumors. *Jpn J Clin Oncol*. 2015;45(12):1097–1102.
43. Tan AR, Yang X, Berman A, et al. Phase I trial of the cyclin-dependent kinase inhibitor flavopiridol in combination with docetaxel in patients with metastatic breast cancer. *Clin Cancer Res*. 2004;10(15):5038–5047.
44. Asghar U, Witkiewicz AK, Turner NC, Knudsen ES. The history and future of targeting cyclin-dependent kinases in cancer therapy. *Nat Rev Drug Discov*. 2015;14(2):130–146.
45. Criscitiello C, Viale G, Esposito A, Curigliano G. Dinaciclib for the treatment of breast cancer. *Expert Opin Investig Drugs*. 2014;23(9):1305–1312.
46. Fry DW, Harvey PJ, Keller PR, et al. Specific inhibition of cyclin-dependent kinase 4/6 by PD 0332991 and associated antitumor activity in human tumor xenografts. *Mol Cancer Ther*. 2004;3(11):1427–1438.
47. Pfizer. IBRANCE, FDA drug sheet. Available at: http://www.accessdata.fda.gov/drugsatfda_docs/label/2015/207103s000lbl.pdf. Accessed April 23, 2016.
48. Rihani A, Vandesompele J, Speleman F, Van Maerken T. Inhibition of CDK4/6 as a novel therapeutic option for neuroblastoma. *Cancer Cell Int*. 2015;15(1):76.
49. Schröder LBW, McDonald KL. CDK4/6 inhibitor PD0332991 in glioblastoma treatment: does it have a future? *Front Oncol*. 2015;5:259.
50. Li C, Qi L, Bellail AC, Hao C, Liu T. PD-0332991 induces G1 arrest of colorectal carcinoma cells through inhibition of the cyclin-dependent kinase-6 and retinoblastoma protein axis. *Oncol Lett*. 2014;7(5):1673–1678.
51. Sathe A, Koshy N, Schmid SC, et al. CDK4/6 inhibition controls proliferation of bladder cancer and transcription of RB1. *J Urol*. 2016;195(3):771–779.
52. Huang S, Ye H, Guo W, et al. CDK4/6 inhibitor suppresses gastric cancer with CDKN2A mutation. *Int J Clin Exp Med*. 2015;8(7):11692–11700.
53. Perez M, Muñoz-Galván S, Jiménez-García MP, Marín JJ, Carnero A. Efficacy of CDK4 inhibition against sarcomas depends on their levels of CDK4 and p16ink4 mRNA. *Oncotarget*. 2015;6(38):40557–40574.
54. Finn RS, Dering J, Conklin D, et al. PD 0332991, a selective cyclin D kinase 4/6 inhibitor, preferentially inhibits proliferation of luminal estrogen receptor-positive human breast cancer cell lines in vitro. *Breast Cancer Res*. 2009;11(5):R77.
55. Bosco EE, Knudsen ES. RB in breast cancer: at the crossroads of tumorigenesis and treatment. *Cell Cycle*. 2007;6(6):667–671.
56. Dean JL, Thangavel C, McClendon AK, Reed CA, Knudsen ES. Therapeutic CDK4/6 inhibition in breast cancer: key mechanisms of response and failure. *Oncogene*. 2010;29(28):4018–4032.
57. Morikawa A, Henry NL. Palbociclib for the treatment of estrogen receptor-positive, HER2-negative metastatic breast cancer. *Clin Cancer Res*. 2015;21(16):3591–3596.
58. Qin G, Xu F, Qin T, et al. Palbociclib inhibits epithelial-mesenchymal transition and metastasis in breast cancer via c-Jun/COX-2 signaling pathway. *Oncotarget*. 2015;6(39):41794–41808.
59. Bocca C, Ievolella M, Autelli R, et al. Expression of Cox-2 in human breast cancer cells as a critical determinant of epithelial-to-mesenchymal transition and invasiveness. *Expert Opin Ther Targets*. 2014;18(2):121–135.
60. Taube JH, Herschkowitz JI, Komurov K, et al. Core epithelial-to-mesenchymal transition interactome gene-expression signature is associated with claudin-low and metaplastic breast cancer subtypes. *Proc Natl Acad Sci U S A*. 2010;107(35):15449–15454.
61. Anders L, Ke N, Hydbring P, et al. A systematic screen for CDK4/6 substrates links FOXM1 phosphorylation to senescence suppression in cancer cells. *Cancer Cell*. 2011;20(5):620–634.
62. Parrish KE, Pokorny J, Mittapalli RK, Bakken K, Sarkaria JN, Elmquist WF. Efflux transporters at the blood-brain barrier limit delivery and efficacy of cyclin-dependent kinase 4/6 inhibitor palbociclib (PD-0332991) in an orthotopic brain tumor model. *J Pharmacol Exp Ther*. 2015;355(2):264–271.
63. de Gooijer MC, Zhang P, Thota N, et al. P-glycoprotein and breast cancer resistance protein restrict the brain penetration of the CDK4/6 inhibitor palbociclib. *Invest New Drugs*. 2015;33(5):1012–1019.
64. Steger GG, Gnant M, Bartsch R. Palbociclib for the treatment of postmenopausal breast cancer – an update. *Expert Opin Pharmacother*. 2016;17(2):255–263.
65. Schwartz GK, LoRusso PM, Dickson MA, et al. Phase I study of PD 0332991, a cyclin-dependent kinase inhibitor, administered in 3-week cycles (schedule 2/1). *Br J Cancer*. 2011;104(12):1862–1868.
66. Flaherty KT, LoRusso PM, DeMichele A, et al. Phase I, dose-escalation trial of the oral cyclin-dependent kinase 4/6 inhibitor PD 0332991, administered using a 21-day schedule in patients with advanced cancer. *Clin Cancer Res*. 2012;18(2):568–576.
67. DeMichele A, Clark AS, Tan KS, et al. CDK 4/6 inhibitor palbociclib (PD0332991) in Rb+ advanced breast cancer: phase II activity, safety, and predictive biomarker assessment. *Clin Cancer Res*. 2015;21(5):995–1001.
68. VanArsdale T, Boshoff C, Arndt KT, Abraham RT. Molecular pathways: targeting the cyclin D-CDK4/6 axis for cancer treatment. *Clin Cancer Res*. 2015;21(13):2905–2910.
69. Finn R, Hurvitz S, Allison M, et al. Phase I Study of PD 0332991, a Novel, Oral, Cyclin-D Kinase (CDK) 4/6 Inhibitor in Combination with Letrozole, for First-Line Treatment of Metastatic Post-Menopausal, Estrogen Receptor-Positive (ER+), Human Epidermal Growth Factor Receptor 2 (HER2)-Negati. *Cancer Res*. 2009;69(24 Supplement):5069–5069.
70. Dhillon S. Palbociclib: first global approval. *Drugs*. 2015;75(5):543–551.
71. Dickson MA, Tap WD, Keohan ML, et al. Phase II trial of the CDK4 inhibitor PD0332991 in patients with advanced CDK4-amplified well-differentiated or dedifferentiated liposarcoma. *J Clin Oncol*. 2013;31(16):2024–2028.
72. Turner NC, Ro J, André F, et al. Palbociclib in hormone-receptor-positive advanced breast cancer. *N Engl J Med*. 2015;373(3):209–219.
73. Dean JL, McClendon AK, Knudsen ES. Modification of the DNA damage response by therapeutic CDK4/6 inhibition. *J Biol Chem*. 2012;287(34):29075–29087.
74. Roberts PJ, Bisi JE, Strum JC, et al. Multiple roles of cyclin-dependent kinase 4/6 inhibitors in cancer therapy. *J Natl Cancer Inst*. 2012;104(6):476–487.
75. Clark AS, O'Dwyer PJ, Heitjan D, et al. A phase I trial of palbociclib and paclitaxel in metastatic breast cancer. *J Clin Oncol*. 2014;32(suppl; abstr 527):5s.